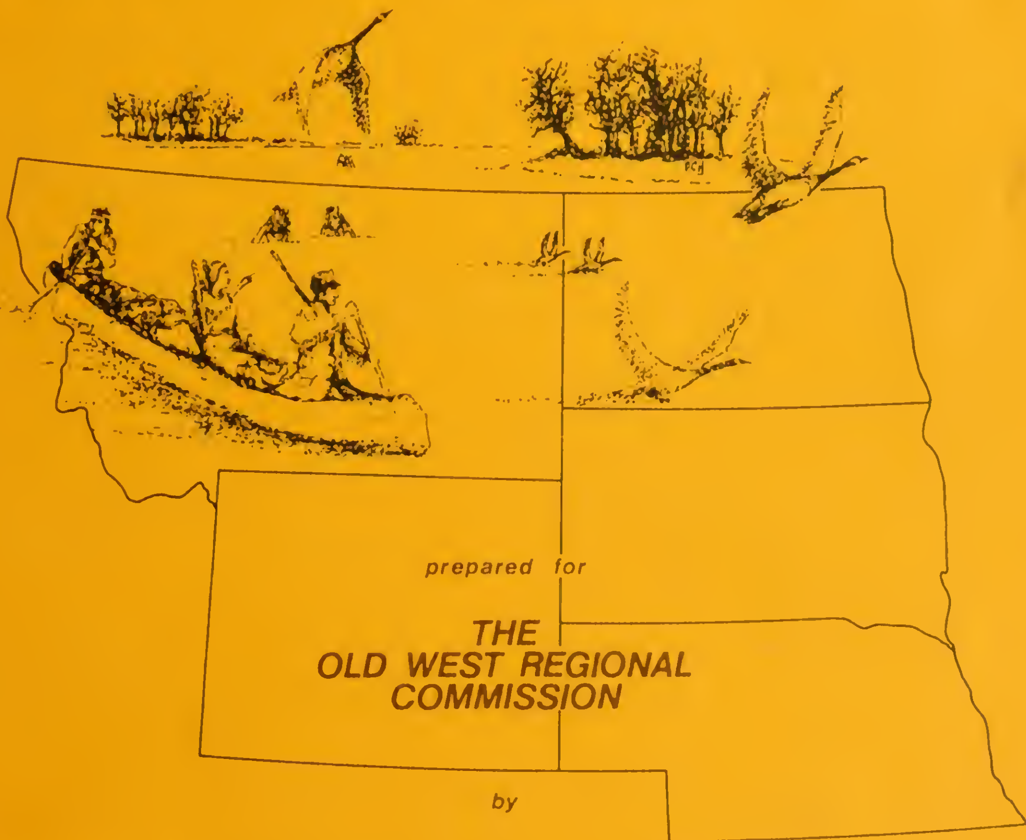
Future development projections and hydrologic modeling in the Yellowstone River Basin, Montana

YELLOWSTONE IMPACT STUDY

TECHNICAL REPORT NO. 1



prepared for

THE
OLD WEST REGIONAL
COMMISSION

by

DNRC WATER RESOURCES DIVISION — JULY 1977

MONTANA DEPARTMENT OF NATURAL RESOURCES & CONSERVATION

Future development projections and hydrologic modeling in the Yellowstone River Basin, Montana

by

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YELLOWSTONE IMPACT STUDY

conducted by the
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July 1977

The Old West Regional Commission is a Federal-State partnership designed to solve regional economic problems and stimulate orderly economic growth in the states of Montana, Nebraska, North Dakota, South Dakota and Wyoming. Established in 1972 under the Public Works and Economic Development Act of 1965, it is one of seven identical commissions throughout the country engaged in formulating and carrying out coordinated action plans for regional economic development.

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FOREWORD

The Old West Regional Commission wishes to express its appreciation for this report to the Montana Department of Natural Resources and Conservation, and more specifically to those Department staff members who participated directly in the project and in preparation of various reports, to Dr. Kenneth A. Blackburn of the Commission staff who coordinated the project, and to the subcontractors who also participated. The Yellowstone Impact Study was one of the first major projects funded by the Commission that was directed at investigating the potential environmental impacts relating to energy development. The Commission is pleased to have been a part of this important research.

George D. McCarthy
Federal Cochairman

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Abbreviations used in this report

af	acre-feet
af/acre	acre-feet per acre
af/y	acre-feet per year
b/d	barrels per day
cfs	cubic feet per second
cm	centimeter
FAA	Federal Aviation Authority
ft	feet
gal/d/pers	gallons per day per person
ha	hectare
hm^3	cubic hectometer
hm^3/y	cubic hectometers per year
hr	hour
in	inch
kg	kilogram
km	kilometer
kwh	kilowatt hour
lb	pound
LMA	Labor Market Area
m	meter
m^3/sec	cubic meters per second
M.C.R.	mean cover rating
mg/l	milligram per liter
mi	mile
millimhos/cm	unit of electrical conductivity per centimeter
mmaf	million acre-feet
mmcfd	million cubic feet per day
mmt/y	million tons per year
mw	megawatts
NGPRP	Northern Great Plains Resource Program
SMSA	standard metropolitan statistical area
SSARR	Steamflow Synthesis and Reservoir Regulation
SWP	State Water Planning Model
t/d	tons per day
tdh	total dynamic head
TDS	total dissolved salts
USGS	United State Geological Survey
whc	water holding capacity

Preface

THE RIVER

The Yellowstone River Basin of southeastern Montana, northern Wyoming, and western North Dakota encompasses approximately 180,000 km^2 (71,000 square miles), 92,200 (35,600) of them in Montana. Montana's portion of the basin comprises 24 percent of the state's land; where the river crosses the border into North Dakota, it carries about 8.8 million acre-feet of water per year, 21 percent of the state's average annual outflow. The mainstem of the Yellowstone rises in northwestern Wyoming and flows generally northeast to its confluence with the Missouri River just east of the Montana-North Dakota border; the river flows through Montana for about 550 of its 680 miles. The major tributaries, the Boulder, Stillwater, Clarks Fork, Bighorn, Tongue, and Powder rivers, all flow in a northerly direction. The western part of the basin is part of the middle Rocky Mountains physiographic province; the eastern section is located in the northern Great Plains (Rocky Mountain Association of Geologists 1972).

THE CONFLICT

Historically, agriculture has been Montana's most important industry. In 1975 over 40 percent of the primary employment in Montana was provided by agriculture (Montana Department of Community Affairs 1976). In 1973, a good year for agriculture, the earnings of labor and proprietors involved in agricultural production in the fourteen counties that approximate the Yellowstone Basin were over $141 million, as opposed to $13 million for mining and $55 million for manufacturing. Cash receipts for Montana's agricultural products more than doubled from 1968 to 1973. Since that year, receipts have declined because of unfavorable market conditions; some improvement may be in sight, however. In 1970, over 75 percent of the Yellowstone Basin's land was in agricultural use (State Conservation Needs Committee 1970). Irrigated agriculture is the basin's largest water use, consuming annually about 1.5 million acre-feet (af) of water (Montana DNRC 1977).

There is another industry in the Yellowstone Basin which, though it consumes little water now, may require more in the future, and that is the coal development industry. In 1971, the North Central Power Study (North Central Power Study Coordinating Committee 1971) identified 42 potential power plant sites in the five-state (Montana, North and South Dakota, Wyoming, and Colorado) northern Great Plains region, 21 of them in Montana. These plants, all to be fired by northern Great Plains coal, would generate 200,000 megawatts (mw) of electricity, consume 3.4 million acre-feet per year (mmaf/y) of water, and result in a large population increase. Administrative, economic, legal,

and technological considerations have kept most of these conversion facilities, identified in the North Central Power Study as necessary for 1980, on the drawing board or in the courtroom. There is now no chance of their being completed by that date or even soon after, which will delay and diminish the economic benefits some basin residents had expected as a result of coal development. On the other hand, contracts have been signed for the mining of large amounts of Montana coal, and applications have been approved not only for new and expanded coal mines but also for Colstrip Units 3 and 4, twin 700-mw, coal-fired, electric generating plants. And in July 1979 the U.S. Department of Energy released a study concluding that 36 synthetic fuel plants could be constructed in Montana; together, they would use 468,000 acre-feet of water annually.

In 1975, over 22 million tons of coal were mined in the state, up from 14 million in 1974, 11 million in 1973, and 1 million in 1969. By 1980, even if no new contracts are entered, Montana's annual coal production will be about 35 million tons. Coal reserves, estimated at over 50 billion economically strippable tons (Montana Energy Advisory Council 1976), pose no serious constraint to the levels of development projected by this study, which range from 186.7 to 462.8 million tons stripped in the basin annually by the year 2000. Strip mining itself involves little use of water. How important the energy industry becomes as a water user in the basin will depend on: 1) how much of the coal mined in Montana is exported, and by what means, and 2) by what process and to what end product the remainder is converted within the state. If conversion follows the patterns projected in this study, the energy industry will use from 48,350 to 326,740 af of water annually by the year 2000.

A third consumptive use of water, municipal use, is also bound to increase as the basin population increases in response to increased employment opportunities in agriculture and the energy industry.

Can the Yellowstone River satisfy all of these demands for her water? Perhaps in the mainstem. But the tributary basins, especially the Bighorn, Tongue, and Powder, have much smaller flows, and it is in those basins that much of the increased agricultural and industrial water demand is expected.

Some impacts could occur even in the mainstem. What would happen to water quality after massive depletions? How would a change in water quality affect existing and future agricultural, industrial, and municipal users? What would happen to fish, furbearers, and migratory waterfowl that are dependent on a certain level of instream flow? Would the river be as attractive a place for recreation after dewatering?

One of the first manifestations of Montana's growing concern for water in the Yellowstone Basin and elsewhere in the state was the passage of significant legislation. The Water Use Act of 1973, which, among other things, mandates the adjudication of all existing water rights and makes possible the reservation of water for future beneficial use, was followed by the Water Moratorium Act of 1974, which delayed action on major applications for Yellowstone Basin water for three years. The moratorium, by any standard a bold action, was prompted by a steadily increasing rush of applications and filings for water (mostly for industrial use) which, in two tributary basins to the Yellowstone, exceeded supply. The DNRC's intention

during the moratorium was to study the basin's water and related land resources, as well as existing and future need for the basin's water, so that the state would be able to proceed wisely with the allocation of that water. The study which resulted in this series of reports was one of the fruits of that intention.

THE STUDY

The Yellowstone Impact Study, conducted by the Water Resources Division of the Montana Department of Natural Resources and Conservation and financed by the Old West Regional Commission, was designed to evaluate the potential physical, biological, and water use impacts of water withdrawals and water development on the middle and lower reaches of the Yellowstone River Basin in Montana. The study's plan of operation was to project three possible levels of future agricultural, industrial, and municipal development in the Yellowstone Basin and the streamflow depletions associated with that development. Impacts on river morphology and water quality were then assessed, and, finally, the impacts of altered streamflow, morphology, and water quality on such factors as migratory birds, furbearers, recreation, and existing water users were analyzed.

The study began in the fall of 1974. By its conclusion in December of 1976, the information generated by the study had already been used for a number of moratorium-related projects--the EIS on reservations of water in the Yellowstone Basin, for example (Montana DNRC 1976). The study resulted in a final report summarizeing all aspects of the study and in eleven specialized technical reports:

Report No. 1	Future Development Projections and Hydrologic Modeling in the Yellowstone River Basin, Montana.
Report No. 2	The Effect of Altered Streamflow on the Hydrology and Geomorphology of the Yellowstone River Basin, Montana.
Report No. 3	The Effect of Altered Streamflow on the Water Quality of the Yellowstone River Basin, Montana.
Report No. 4	The Adequacy of Montana's Regulatory Framework for Water Quality Control
Report No. 5	Aquatic Invertebrates of the Yellowstone River Basin, Montana.
Report No. 6	The Effect of Altered Streamflow on Furbearing Mammals of the Yellowstone River Basin, Montana.
Report No. 7	The Effect of Altered Streamflow on Migratory Birds of the Yellowstone River Basin, Montana.

Report No. 8	The Effect of Altered Streamflow on Fish of the Yellowstone and Tongue Rivers, Montana.
Report No. 9	The Effect of Altered Streamflow on Existing Municipal and Agricultural Users of the Yellowstone River Basin, Montana.
Report No. 10	The Effect of Altered Streamflow on Water-Based Recreation in the Yellowstone River Basin, Montana.
Report No. 11	The Economics of Altered Streamflow in the Yellowstone River Basin, Montana.

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DNRC personnel providing assistance were George Cawlfield, who helped with the hydrologic modeling reported in Part II and reviewed and revised Part II; John Jarvie, who also helped with Part II; Glen Smith, who superivsed the preparation of the irrigable land projections, and Elna Tannehill, who helped with the economic analysis used in those projections; Gary Fritz, administrator of DNRC's Water Resources Division, who provided guidance and review; Mark Nicholson, Ron Schleyer, Shari Meats, Marianne Melton, and Karen Renne, who performed editing tasks; and Janet Cawlfield, Lynda Howell, and Kris MacIntyre, typists. Graphics were coordinated and performed by Gary Wolf, with the assistance of Dan Nelson. The cover was designed and executed by D.C. Howard.

Introduction

DEVELOPMENT PROJECTIONS

The principal objective of the Yellowstone Impact Study was to evaluate potential environmental impacts resulting from future water development likely to occur on the Yellowstone River. Achievement of this objective was handicapped throughout the study by two inherent problems. First, the Yellowstone, because it is a free-flowing river, is not controllable. Researchers were unable to alter the streamflows and observe changes. Thus, all studies had to be made under the circumstances nature provided, which were less than ideal for a low-flow study such as this--1975 was a year of record high flows and 1976 a year of moderate flows.

A second problem, a subject of this report, was the imperfect knowledge of the magnitude and type of future water developments. The purpose of this part of the Yellowstone Impact Study was to resolve that problem by projecting future resource development and economic growth in the basin and the amount of water that development would require. The material presented in this report is basic to the entire study; the other ten technical reports project the types and amounts of impact that would be expected in the Yellowstone Basin if the water depletions projected in this report were to occur.

If major water developments occur, they are expected to be of two types: agricultural and energy-industrial. (It was assumed that future agricultural water use will be for irrigation.) Municipal water use, to be determined by the two major types of development, will be one order of magnitude less. Part I of this report projects the amount of development of each of these three types that might occur in the basin and how much water would be required. Part II projects, through a computer simulation, what the streamflow in the Yellowstone River and its major tributaries would be if the projected amounts of water were withdrawn.

The projections made throughout this report are projections of what might happen, based on particular assumptions; they are not predictions of what will happen. The irrigation projections are uncertain because of the unknown future of many factors, especially crop prices. The energy development projections are even more uncertain. Although the extent of the coal resource is well known, the future demand for development of that resource is not, and no attempt is made in this report to predict future demand for coal. Rather, a high level of development is defined as the scenario that would occur if the State of Montana were to actively promote coal development.

Regardless of the rigor of the prediction methodology, it must be based on numerous assumptions that are plagued with uncertainty. Only one of these assumptions may turn out to involve the controlling factor, but it is impossible at this time to identify that factor, let alone the demand's

elasticity to that factor. Rather, this study assumed a "What if . . ?" approach. If coal development occurs at the high level, what will be the impacts of that level of development? If they are unacceptable, then the state can attempt to constrain the development at a lower level through institutional means. If it is naive to assume that the state can and will exert such control, then the whole exercise is fruitless.

BASIN DIVISION

To facilitate this study, the Yellowstone River Basin was divided into the following nine subbasins[1]:

1) The Upper Yellowstone Subbasin, which consists of the basins of the Yellowstone mainstem from the Montana-Wyoming border to Laurel (43B and 43QJ), the Shields River (43A), the Boulder River (43BJ), Sweet Grass Creek (43BV), and the Stillwater River (43C);

2) The Clarks Fork Yellowstone Subbasin (43D);

3) The Billings Area Subbasin, which consists of the basins of the Yellowstone River (43Q) and Pryor Creek (43E);

4) The Bighorn Subbasin, which includes the basins of the Bighorn (43P) and Little Bighorn rivers (43O);

5) The Mid-Yellowstone Subbasin, which consists of the basins of Rosebud Creek (42A) and of the Yellowstone mainstem between the confluences of the Bighorn and Yellowstone rivers (42KJ);

6) The Tongue Subbasin (42B and 42C);

7) The Kinsey Area Subbasin, the smallest of the nine subbasins considered in this study, which consists of the basin of the Yellowstone mainstem between the confluences of the Tongue and Yellowstone rivers and the Powder and Yellowstone rivers (42K);

8) The Powder Subbasin, which includes the basins of the Powder (42J) and Little Powder rivers (42I); and

9) The Lower Yellowstone Subbasin, which consists of the basins of O'Fallon Creek (42L) and of the Yellowstone mainstem from the confluence of the Powder and Yellowstone rivers to the Montana-North Dakota border (42M).

Figure 1 shows the nine subbasins with their boundaries. The subbasins approximate the basins of the major tributaries of the Yellowstone River, allowing each of the major tributaries to be modeled for the Yellowstone Impact Study.

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[1]The numbers in parentheses correspond to the basin numbers used to indicate hydrologic basins in An Atlas of Water Resources in Montana by Hydrologic Basins (MWRB 1970).

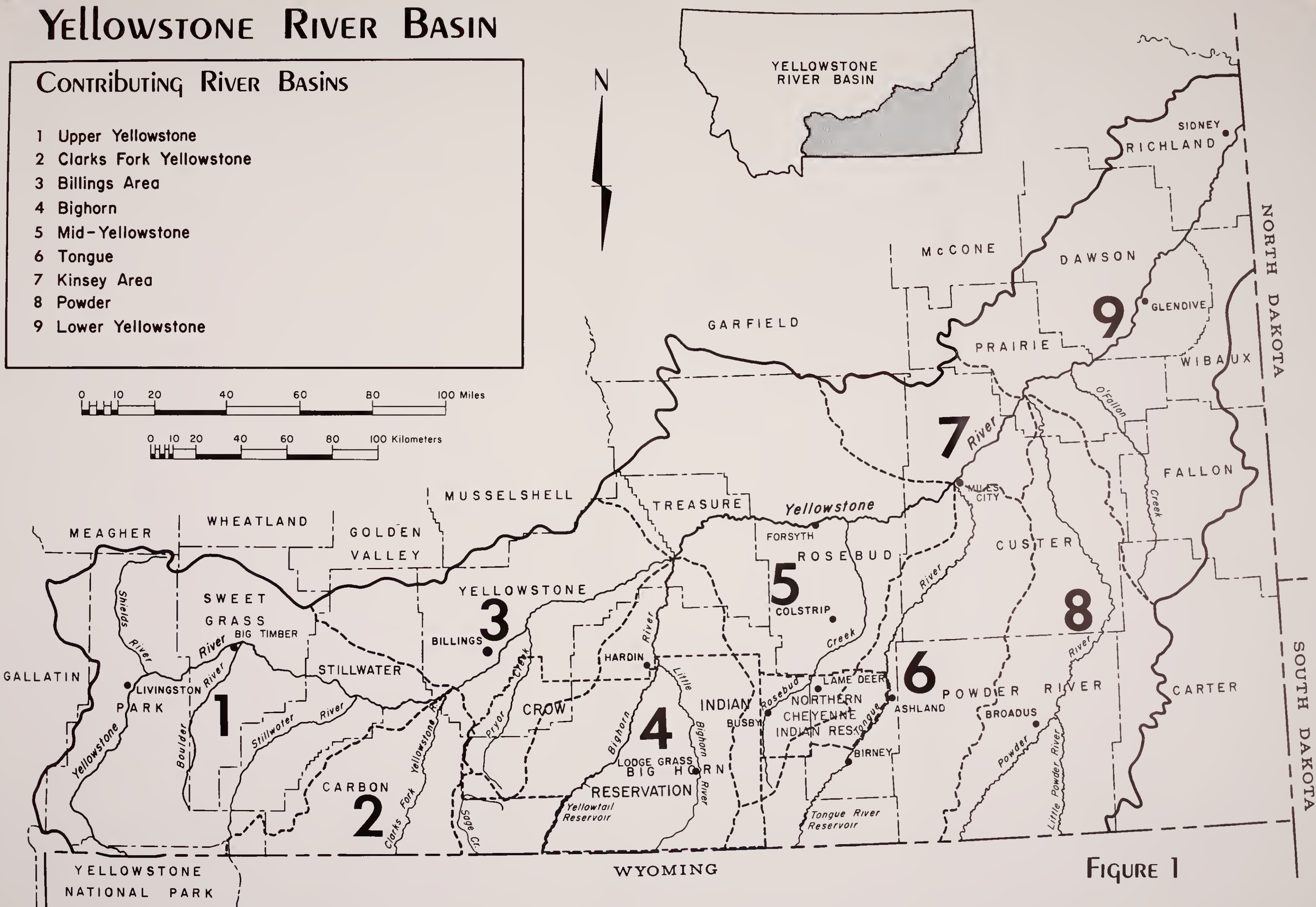
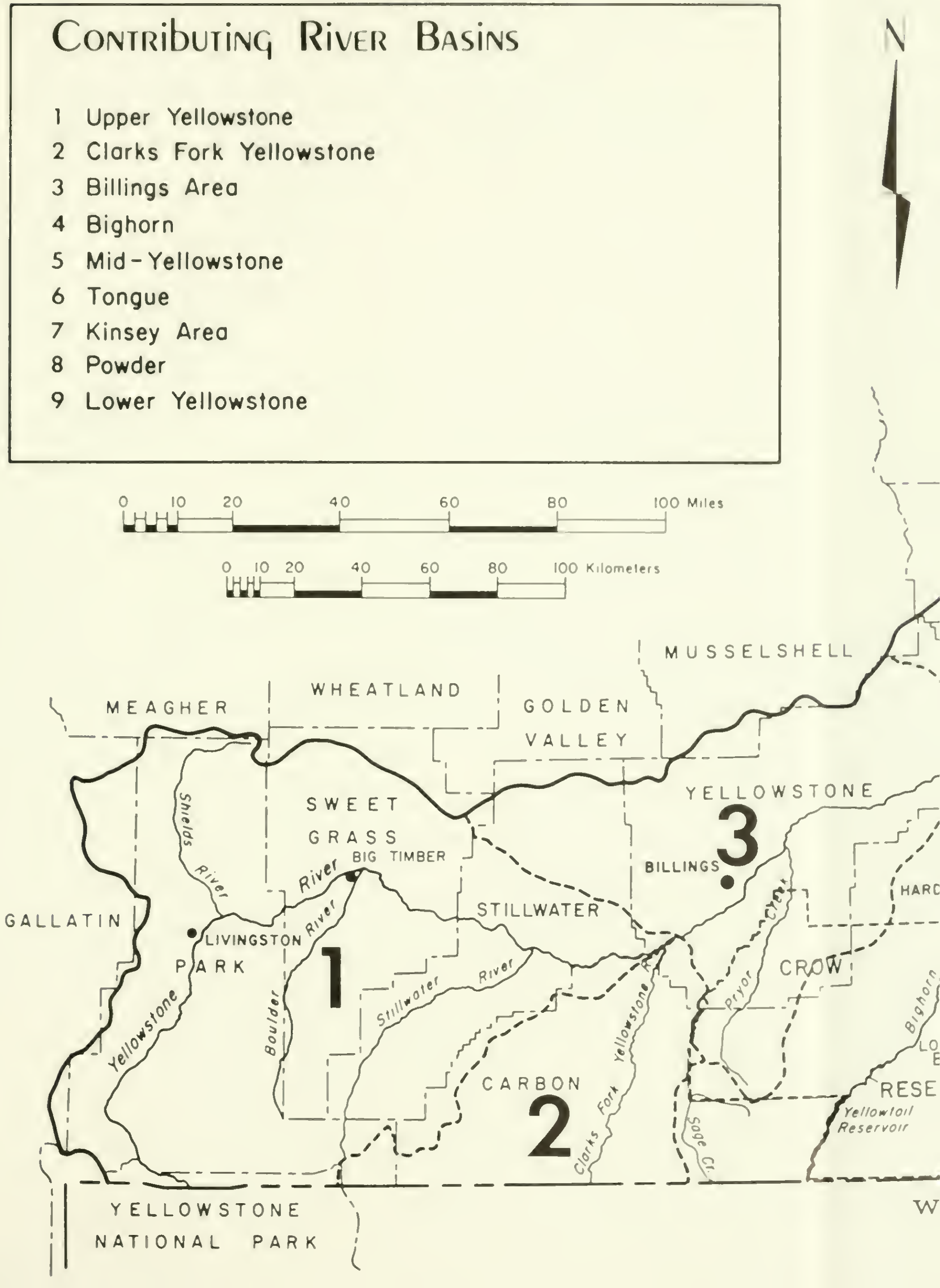

YELLOWSTONE RIVER BASIN
CONTRIBUTING RIVER BASINS
1 Upper Yellowstone
2 Clarks Fork Yellowstone
3 Billings Area
4 Bighorn
5 Mid-Yellowstone
6 Tongue
7 Kinsey Area
8 Powder
9 Lower Yellowstone
0 10 20 40 60 80 100 Miles
0 10 20 40 60 80 100 Kilometers
N
YELLOWSTONE RIVER BASIN
SIDNEY
RICHLAND
McCONE
DAWSON
NORTH DAKOTA
GARFIELD
GLENDIVE
PRAIRIE
WIBAUX
O'Fallon
River
MILES CITY
FALLON
MUSSELSHELL
TREASURE
Yellowstone
Creek
WHEATLAND
MEAGHER
GOLDEN VALLEY
FORSYTH
ROSEBUD
CUSTER
SWEET GRASS
YELLOWSTONE
COLSTRIP
Shields River
BIG TIMBER
BILLINGS
Creek
GALLATIN
HARDIN
Little
LAME DEER
POWDER RIVER
CARTER
LIVINGSTON
STILLWATER
CROW
INDIAN
NORTHERN CHEYENNE INDIAN RES.
ASHLAND
BROADUS
SOUTH DAKOTA
PARK
Stillwater River
Pryor
Bighorn
BUSBY
Tongue
Yellowstone
Boulder
CARBON
LODGE GRASS
BIG HORN
BIRNEY
Powder
Little Powder River
Clarks Fork
Sage Cr.
RESERVATION
Yellowtail Reservoir
Tongue River Reservoir
YELLOWSTONE NATIONAL PARK
WYOMING

FIGURE 1

Yellowstone River Basin

Contributing River Basins

1 Upper Yellowstone
2 Clarks Fork Yellowstone
3 Billings Area
4 Bighorn
5 Mid-Yellowstone
6 Tongue
7 Kinsey Area
8 Powder
9 Lower Yellowstone



Part 1

Future water use projections

by

Bob Anderson
Phil Threlkeld
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Projections of coal production for energy

The low-sulfur coal in southeastern Montana currently is in demand. The increasing world price of oil, decreasing domestic supplies of crude oil and natural gas, and the goal of United States energy self-sufficiency have increased the market value of many domestic coal reserves, including Montana's.

Averiet (1974) estimated that coal reserves in Montana might be as high as 448.6 billion tons of lignite, subbituminous, and bituminous coal. Estimates by the Bureau of Reclamation (USDI 1972) indicate that approximately 75 percent of this total lies within 1,000 ft of the surface. The Montana reserve is part of the vast Fort Union coal region (considered the world's largest), which contains approximately 40 percent of the United States coal reserve (Montana Coal Task Force 1973) and underlies parts of western North Dakota, northwestern South Dakota, northeastern Wyoming, southeastern Saskatchewan, and eastern Montana.

Strip mining is used to recover these coal reserves. Economically, underground mining has a weak competitive position in Montana. Compared to strip mining, capital requirements are higher for underground mining, and productivity per miner is low. The actual cost of mining is, as a result, far higher.

In the West, whether a coal deposit is strippable commonly is determined according to the depth criteria in table 1. Matson (1974) estimated that 42.5 billion tons of strippable coal underlies eastern Montana. Figure 2 locates strippable coal reserves in the Montana portion of the Fort Union coal region.

Table 1. Definition of strippable coal.

Thickness of Strippable Beds (ft)	Maximum Overburden Depth (ft)
0 - 10	0 - 100
10 - 25	0 - 150
25 - 40	0 - 200
more than 40	0 - 250

SOURCE: Montana College of Mineral Science and Technology 1973

Because of the low cost of strip mining, use of western coal reserves for power and fuel is highly profitable for mining companies. There are three major markets expected to buy Montana coal from the companies: 1) power-plant operators in the South, Midwest, and Pacific Northwest; 2) producers of synthetic fuels from coal at mine-mouth conversion facilities, and 3) power-plant operators at mine-mouth plants in Montana. This report does not attempt to estimate exactly the demand these three markets might generate for southeastern Montana coal, but postulates certain quantitative increases in production as the general response to demand for energy.

METHODS

This study develops coal-production projections for energy development in Montana's portion of the Yellowstone River Basin. Three levels of development are postulated for five consuming sectors of the national economy: household and commercial, industrial, electrical generation, synthetic fuel, and export for processing or consumption elsewhere. The projections span the years 1975 through 2000. The intent is not to predict the future but rather to present alternative futures (levels of development) in coal production.

After postulating levels of coal development, the study calculated industrial water use requirements to aid in determining the potential impacts of altered streamflows on existing consumers of water and on recreation, water quality, the ecosystem, and the economy (see reports 2 through 11 in this series).

PREVIOUS PROJECTIONS

A number of private organizations and government agencies have projected coal production and related economic development in Montana. A few of those studies are identified below.

1) The Federal Energy Administration's Project Independence Report (1974) constructed a model of supply and demand for coal in the Northern Great Plains. Because the assumptions on which the model is based are unknown, comparison or use of the reported data is difficult.

2) A Northern Great Plains Resource Program (NGPRP) work group issued a national report on regional energy considerations in 1974, which presented a series of coal-development projections for the NGPRP. Some of those projections are used extensively in this report and are discussed where applicable. The NGPRP is intergovernmental and involves the states of the Northern Great Plains region (Montana, Wyoming, North Dakota, South Dakota, and Nebraska) and three federal agencies (Environmental Protection Agency, Department of the Interior, and Department of Agriculture) with responsibilities for problems that might arise from coal and energy development in the region.

Yellowstone River Basin

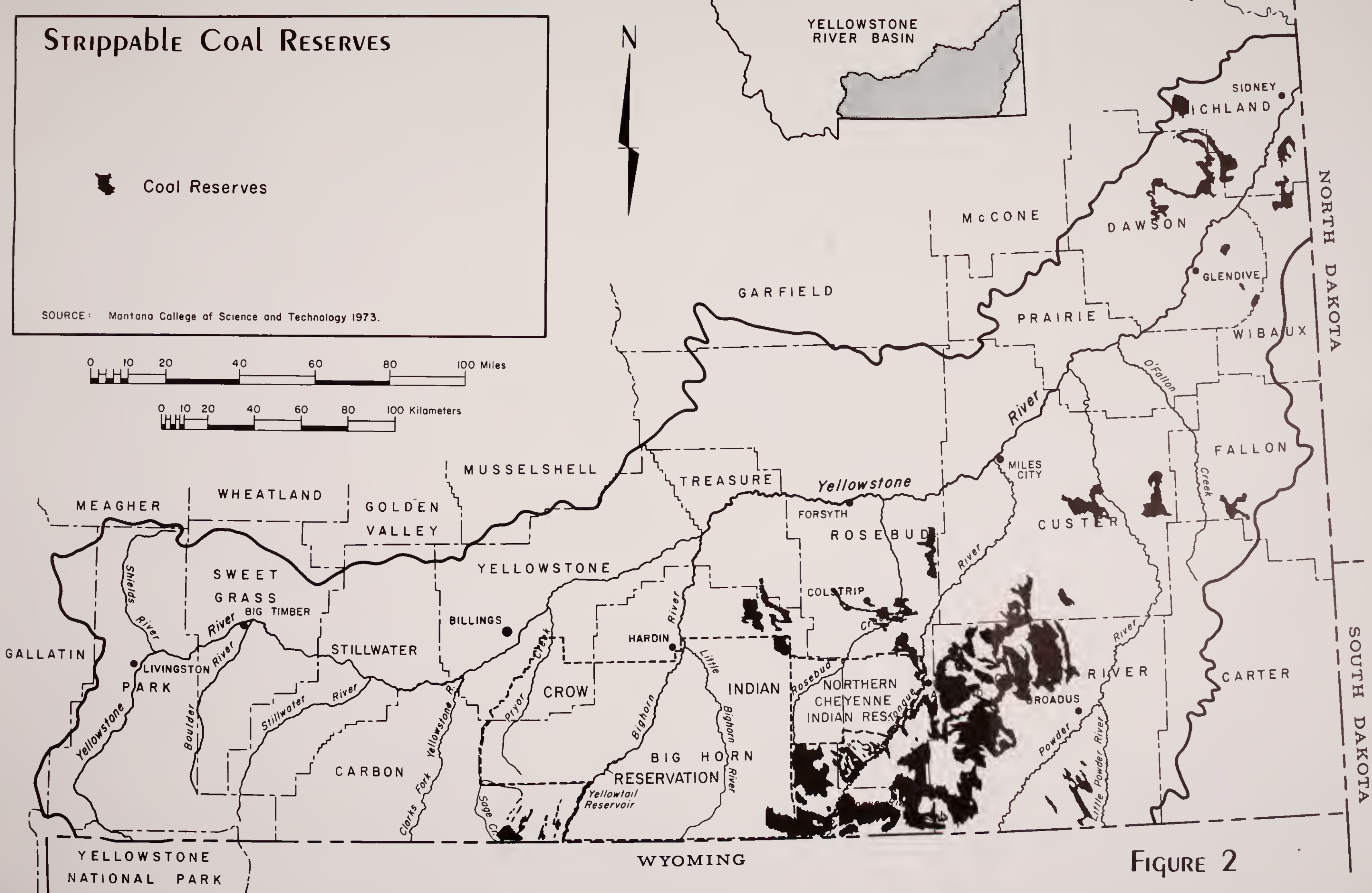


Figure 2

Because of the low cost of strip mining, use of western coal reserves for power and fuel is highly profitable for mining companies. There are three major markets expected to buy Montana coal from the companies: 1) power-plant operators in the South, Midwest, and Pacific Northwest; 2) producers of synthetic fuels from coal at mine-mouth conversion facilities, and 3) power-plant operators at mine-mouth plants in Montana. This report does not attempt to estimate exactly the demand these three markets might generate for southeastern Montana coal, but postulates certain quantitative increases in production as the general response to demand for energy.

METHODS

This study develops coal-production projections for energy development in Montana's portion of the Yellowstone River Basin. Three levels of development are postulated for five consuming sectors of the national economy: household and commercial, industrial, electrical generation, synthetic fuel, and export for processing or consumption elsewhere. The projections span the years 1975 through 2000. The intent is not to predict the future but rather to present alternative futures (levels of development) in coal production.

After postulating levels of coal development, the study calculated industrial water use requirements to aid in determining the potential impacts of altered streamflows on existing consumers of water and on recreation, water quality, the ecosystem, and the economy (see reports 2 through 11 in this series).

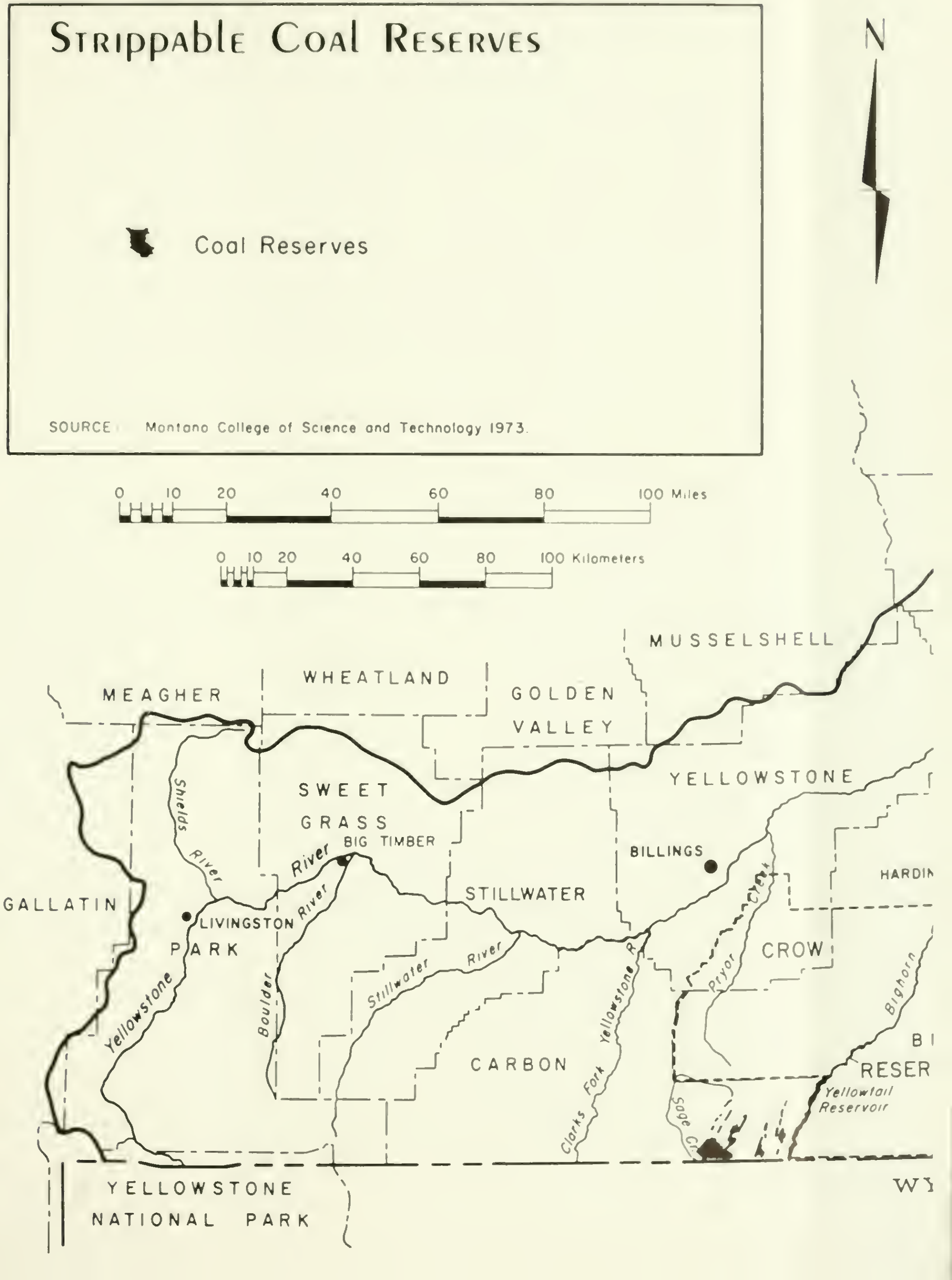
PREVIOUS PROJECTIONS

A number of private organizations and government agencies have projected coal production and related economic development in Montana. A few of those studies are identified below.

1) The Federal Energy Administration's Project Independence Report (1974) constructed a model of supply and demand for coal in the Northern Great Plains. Because the assumptions on which the model is based are unknown, comparison or use of the reported data is difficult.

2) A Northern Great Plains Resource Program (NGPRP) work group issued a national report on regional energy considerations in 1974, which presented a series of coal-development projections for the NGPRP. Some of those projections are used extensively in this report and are discussed where applicable. The NGPRP is intergovernmental and involves the states of the Northern Great Plains region (Montana, Wyoming, North Dakota, South Dakota, and Nebraska) and three federal agencies (Environmental Protection Agency, Department of the Interior, and Department of Agriculture) with responsibilities for problems that might arise from coal and energy development in the region.

Yellowstone River Basin



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3) The Montana University Coal Demand Study (MUCDS) report entitled _Projections of Northern Great Plains Coal Mining and Energy Conversion Development 1975-2000 A.D._ considered demand for Northern Great Plains Resource Program coal associated with two primary facilities--electric generation and synthetic natural gas. The MUCDS attempted to (1) identify what factors will influence NGP coal development, (2) indicate the key variables determining development, and (3) establish quantitatively how the levels of development would be altered if the variables were to change. The MUCDS projections for synthetic natural gas production are reflected in the projections of the Yellowstone Impact Study.

4) In September 1975, the Missouri River Basin Commission began the Yellowstone Level B Study, a two-year planning study to develop general information on water and related land resources in the Yellowstone River Basin and adjacent coal areas. The Commission hired the Harza Engineering Company to develop three alternative coal-mining and energy-conversion levels for the years 1985 and 2000 reflecting demand and supply of energy nationally and within the Yellowstone Basin.

ENERGY-DEVELOPMENT ALTERNATIVES

This report incorporates many of the aforementioned coal development estimates to provide a fresh and realistic estimate of potential levels of coal and energy development in southeastern Montana and the rest of the Yellowstone Basin. As with any projection on this subject, predicting the levels of development is speculation because of the major unknowns--future demand and cost for coal, and the extent that public policy will allow coal development to proceed.

Because the number of possible alternative futures is great, this study chose three possibilities that might arise from the influences on coal development in the Yellowstone River Basin. Two of these--low and high levels of development--were chosen to represent limited development and highly advanced development of coal resources. An intermediate alternative fills the gap between the low-level and the advanced-development alternatives.

A fourth and lowest alternative--gradually rising coal production to 1980 and practically stable production thereafter--was examined (see tables 2 and 3), but it is not considered to be a practical possibility in view of the pressures tending to encourage coal development in the United States. Only if alternative sources of energy (such as the sun) or energy conservation prove to be more economically attractive than coal conversion is there likely to be any such leveling off of Montana coal production within a decade. For this study, a gradual rise in coal production is assumed to be inevitable in view of existing coal sales contracts signed by six companies operating in the Yellowstone River Basin.

Alternative levels of development presented here are based on data from the Montana Energy Advisory Council (1974). Existing data were supplemented and updated in response to more recent production figures. Coal

production is given in million short tons (mmt) unless noted otherwise. (A short ton is equal to 2,000 pounds.)

Table 2 displays estimates of coal production for 1975 and 1980 based on existing coal sales contracts signed by the six companies. The coal production tonnages have been reassembled according to two uses: electrical generation in southeastern Montana and export out of Montana. Most coal mined in Montana until 1980 under existing contracts will be shipped out of state for use by Midwestern and Southern utilities in electrical generation.

Table 2. Coal production in 1975 and 1980 in the Yellowstone Basin based on coal sales contracts (mmt).

Coal for Electrical Generation in Montana		
Mining Company	1975	1980
Knife River Coal Co. (for Sidney plant)	0.32	0.30
Western Energy Co. (for Corette plant in Billings)	0.50	0.50
Western Energy Co. (for Colstrip)	0.40	3.20
TOTAL	1.22	4.00
Coal for Export		
Western Energy Co.	4.33	10.00
Decker Coal Co.	8.25	13.90
Westmoreland	4.00	6.50
Peabody	3.00	3.00
Shell Oil Co.	--	8.00
TOTAL	19.58	41.40

Synthetic-fuel facilities could become part of the Montana stabilized coal-production alternative in the year 2000. In meeting the gap between supply and demand for gas, it might be necessary to construct a synthetic gas plant capable of producing 250 million standard cubic feet per day (mmcf/d). It would consume approximately 7.6 mmt of coal per year. The product of stabilized coal production during the remaining years of the century would be consumed in the five major coal-consuming sectors of the national economy as indicated in table 3. In this and all other alternatives, consumption in the household-commercial and industrial sectors is insignificant after 1975 in comparison with the other consuming sectors.

Table 3. Stabilized coal production in the Yellowstone River Basin

Consuming Sector	1971 (Actual)	1975[a] (Actual)	1980	1985	2000
Household and Commercial	0.1	0.2	insig.	insig.	insig.
Industrial	0.1	0.2	insig.	insig.	insig.
Electrical Generation	0.8	0.8	4.0	4.0	4.0
Synthetic Fuel	0	0	0	0	7.6
Exports	6.1	21.0	41.4	41.4	41.4
TOTAL	7.1	22.2	45.4	45.4	53.0

[a]Extrapolated from Montana DNRC 1976, p. 83, table 5.6.

LOW LEVEL OF DEVELOPMENT

The study assumes that under low-level development coal production will be limited to meeting Montana demands and supplying existing and planned delivery contracts. The projections were derived from a combination of data compiled by the Montana Energy Advisory Council (1974), the Northern Great Plains Resource Program (1974b), and by companies planning coal production for export. (Existing data were supplemented or updated since the MEAC and NGPRP studies in response to more recent production figures as they became available.)

Table 4 shows coal production planned for export, by three mining companies through the year 2000. These companies have leases for the coal but are still engaged in planning. Although some contracts are signed, acceptance of environmental impact statements for the mines and agreements on royalties are still pending.

Combining this with information on existing sales contracts (table 2) and coal production forecast by NGPRP (corrected to make it applicable to

Table 4. Planned coal production by company, mine, and year (mmt)

Company and Mine	Production									
	Actual			Planned						
	1976	1977	1978	1980	1981	1982	1983	1984	1985	2000
SHELL OIL CO.[a]										
Youngs Creek	0	0	0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Tanner Creek	0	0	0	2.0	4.0	4.0	4.0	4.0	8.0	8.0
Wolf Mountain	0	0	0	2.0	2.0	4.0	4.0	4.0	4.0	8.0
Squirrel Creek	0	0	0	0	0	0	0	0	2.0	8.0
DECKER COAL CO.										
East Decker	0	0	2.25	6.6	6.6	6.6	6.6	6.6	6.6	6.6
North Extension	0	0	0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
WESTMORELAND										
Crow-Ceded Lands	4.0	4.5	4.5	4.0	4.0	10.0	10.0	10.0	10.0	15.0
TOTAL	4.0	4.5	6.75	24.6	26.6	34.6	34.6	34.6	40.6	55.6

NOTE: Production shown here is in addition to the existing contracts tabulated in table 2. Derived from 1975 data, partially updated in 1979.

[a]The Shell Oil Company (Ireson 1979) says plans for these mines are held in abeyance until litigation and negotiation with the Crow Tribe are complete.

the Yellowstone Basin only) yields a complete projection of coal production to meet low-level consumption demands through the end of the century. It is presented in table 5.

The Yellowstone Impact Study focused in particular on the years 1980, 1985, and 2000. Under the low-level development assumptions, there would be 66 mmt mined for export in 1980; 114 mmt in 1985; and 171 mmt mined for export in 2000.

Electrical generation facilities are projected to consume 4.0 mmt of coal basin-wide in 1985 and 8.0 mmt in the year 2000. Another 7.6 mmt is expected to be consumed by the single coal gasification plant envisioned to be in operation by the end of the century under the assumptions of low-level development. Table 6 indicates that, through 1985, only the Mid-Yellowstone Subbasin would have energy conversion facilities. By 2000, the Tongue Subbasin would have a 500-mw electrical generating plant.

Table 5. Coal production in the Yellowstone Basin under low-level development (mmt).

Consuming Sector	1971 (Actual)	1975 (Actual)	1980[a]	1985[b]	2000[c]
Household-Commercial	0.1	0.2	insig.	insig.	insig.
Industrial	0.1	0.2	insig.	insig.	insig.
Electrical Generation	0.8	0.8	4.0	4.0	8.0
Synthetic Fuels	0	0	0	0	7.6
Export from Montana	6.1	21.0	66.0	114.0	171.1
TOTAL	7.1	22.2	69.8	118.0	186.7

[a]Existing contracts and planned exports.

[b]NGPRP data plus coal exports.

[c]NGPRP data plus coal exports.

Table 7 shows coal production by subbasin during the remaining years of the century under the low-level development projections. The production figures shown in table 5 thus appear in the basin totals for each of the consumptive uses shown in the tables--electrical generation, gasification, production of synthetic crude oil and fertilizer--plus exports. Under the assumptions of low-level coal development in the Yellowstone Basin, export of coal by slurry pipeline would play no part in coal exports through the year 2000.

Table 6. Location of coal conversion facilities through the year 2000, low-level development

	1000-mw Electric Generating Plants	250-mmdfd Synthetic Gas Plants	100,000-b/d Synthetic Crude Plants	2300-t/d Fertilizer Plants
1980				
Mid-Yellowstone	1	0	0	0
All Others	0	0	0	0
TOTAL	1	0	0	0
1985				
Mid-Yellowstone	1	0	0	0
All Others	0	0	0	0
TOTAL	1	0	0	0
2000				
Tongue	0.5	0	0	0
Mid-Yellowstone	1.5	1	0	0
All Others	0	0	0	0
TOTAL	2	1	0	0

Table 7. Coal tonnage location by Yellowstone River subbasins, low-level development, 1980, 1985, 2000 (mmt/y)

Subbasins	Electric Generation	Gasification	Syncrude	Fertilizer	Export[a]	Total
1980						
Tongue	0	0	0	0	29.7	29.7
Mid-Yellowstone	4.0	0	0	0	23.1	27.1
Powder	0	0	0	0	6.6	6.6
Bighorn	0	0	0	0	6.6	6.6
TOTAL	4.0	0	0	0	66.0	70.0
1985						
Tongue	0	0	0	0	51.3	51.3
Mid-Yellowstone	4.0	0	0	0	39.9	43.9
Powder	0	0	0	0	11.4	11.4
Bighorn	0	0	0	0	11.4	11.4
TOTAL	4.0	0	0	0	114.0	118.0
2000						
Tongue	2.0	0	0	0	77.0	79.0
Mid-Yellowstone	6.0	7.6	0	0	59.9	73.5
Powder	0	0	0	0	17.1	17.1
Bighorn	0	0	0	0	17.1	17.1
TOTAL	8.0	7.6	0	0	171.1	186.7

[a]All export at the low level of development was assumed to be by unit train rather than slurry pipeline.

INTERMEDIATE LEVEL OF DEVELOPMENT

The study assumes that under intermediate-level development coal production and energy development will occur midway between the projections for low and high levels of development. The intermediate level of development may or may not be the most likely projection and should be regarded simply as one possibility within the defined range for future coal and energy development.

Coal tonnages that would be mined through the end of the century under assumptions for intermediate-level development are displayed in table 8. The amounts of coal used by the consuming sectors in 1975 are based on data in table 2 on long-term coal contracts. Each estimate for electrical generation, synthetic fuel, or export for 1980, 1985, or 2000 in table 8 is the mean between the low and high levels of development. The study assumes that under intermediate-level coal development, 20 percent of coal exports will be by slurry pipeline by the year 2000.

Table 9 indicates that under intermediate level development, only the Mid-Yellowstone Subbasin would have energy conversion facilities in 1980 and 1985. The trend would be toward gradual additions to the mine-mouth electrical generation capacity of the Mid-Yellowstone Subbasin, with three 1,000-mw generating plants and one 250-mmcf/d synthetic gas plant likely by the year 2000. By that time, there would also be two 1000-mw electrical generating plants in the Tongue River subbasin and one in the Powder River subbasin.

Table 10 shows coal production by subbasin during the remaining years of the century under the intermediate-level development projections The production figures shown in table 8 appear in the basin-wide totals for each of the consumptive uses shown in the table--electrical generation, gasification, production of synthetic crude oil and fertilizer, and exports. By the year 2000, under the assumptions of intermediate-level coal development in the Yellowstone Basin, 20 percent of coal exports would be by slurry pipeline (see "Export" column, table 10).

HIGH LEVEL OF DEVELOPMENT

The high-level of development estimate shows the extent to which development of Yellowstone River Basin coal reserves would be pursued if coal were used to fuel U.S. energy self-sufficiency and if its substitutes--energy conservation, oil, natural gas, nuclear power, and alternative energy sources--were unable to supply substantial shares. Table 11 shows coal production tonnage to meet demand under high-level development.

Table 8. Coal production in the Yellowstone Basin under the intermediate level of development (mmt)

Consuming Sector	1971 (Actual)	1975 (Actual)	1980	1985	2000
Household and Commercial	0.1	0.2	insig	insig	insig
Industrial	0.1	0.2	insig	insig	insig
Electrical Generation	0.8	0.8	4.0	8.0	24.0
Synthetic Fuel	0	0	0	0	7.6
Exports	6.1	21.0	68.6	154.6	293.2
TOTAL	7.1	22.2	72.6	162.6	324.8

Table 9. Location of coal conversion facilities through the year 2000, intermediate level of development

Subbasin	1000-mw Electric Generating Plants	250-mmcf/d Synthetic Gas Plants	1,000-b/d Synthetic Crude Plants	2,300-t/d Fertilizer Plants
		1980		
Mid-Yellowstone	1	0	0	0
All others	0	0	0	0
TOTAL	1	0	0	0
		1985		
Mid-Yellowstone	2	0	0	0
All others	0	0	0	0
TOTAL	2	0	0	0
		2000		
Tongue	2	0	0	0
Mid-Yellowstone	3	1	0	0
Powder	1	0	0	0
All others	0	0	0	0
TOTAL	6	1	0	0

Table 10. Coal tonnage location by Yellowstone River subbasin, intermediate level of development, 1980, 1985, 2000 (mmt/y)

Subbasin	Electric Generation	Gasification	Syncrude	Fertilizer	Export Rail	Export Slurry	Export Total	Total
1980								
Tongue	0	0	0	0	30.8	0	30.8	30.8
Mid-Yellowstone	4.0	0	0	0	24.0	0	24.0	28.0
Powder	0	0	0	0	6.9	0	6.9	6.9
Bighorn	0	0	0	0	6.9	0	6.9	6.9
TOTAL	4.0	0	0	0	68.6	0	68.6	72.6
1985								
Tongue	0	0	0	0	69.5	0	69.5	69.5
Mid-Yellowstone	8.0	0	0	0	54.1	0	54.1	62.1
Powder	0	0	0	0	15.5	0	15.5	15.5
Bighorn	0	0	0	0	15.5	0	15.5	15.5
TOTAL	8.0	0	0	0	154.6	0	154.6	162.6
2000								
Tongue	8.0	0	0	0	105.6	26.4	132.0	140.0
Mid-Yellowstone	12.0	7.6	0	0	73.3	20.5	102.6	122.2
Powder	4.0	0	0	0	23.4	5.9	29.3	33.3
Bighorn	0	0	0	0	23.4	5.9	29.3	29.3
TOTAL	24.0	7.6	0	0	225.7	58.7	293.2	324.8

Table 11. Coal production for consumption under high-level development, Yellowstone Basin (mmt)

Consuming Sector	1971 (Actual)	1975 (Actual)	1980	1985	2000
Household and Commercial	0.1	0.2	insig.	insig.	insig.
Industrial	0.1	0.2	insig.	insig.	insig.
Electrical Generation	0.8	0.8	4.0	8.0	32.0
Synthetic Fuel					
gas	0	0	0	0	22.8
crude	0	0	0	0	36.0
fertilizer	0	0	0	0	3.5
Exports	6.1	21.0	71.4	199.1	368.5
TOTAL	7.1	22.2	75.4	207.1	462.8

The 1980 projection of coal production for electrical generation shown in table 2 is based on coal production data tabulated by the Montana Energy Advisory Council (1974). However, the coal export in 1980 is a combination of the adjusted NGPRP data and recent changes in coal sales contracts. The 1985 projection of coal production for electrical generation is 8.0 mmt, double the 1980 amount, because it was assumed that Colstrip Units 3 and 4 would be in operation by that date. The projection of coal production for export in 1985, 199.1 mmt, was derived from NGPRP projections and from a Missouri River Basin Commission (MRBC) study, Analysis of Energy Projections and Implications for Resource Requirements (1976). High-level coal development estimates are based on assumptions that 20 percent of the coal in 1985 will be exported by slurry, increasing total export capacity to 199.1 mmt. This figure includes coal moving by unit train.

Under high-level development projections for the year 2000, electrical generation would consume 32.0 mmt of coal. This figure is derived from the Western States Water Council's (1974) estimation of production of 8,260 mw of electricity from coal for 1990.

The synthesis of fuel and fertilizer is estimated to require 61.3 mmt of coal by 2000 under high-level development. Approximately 23 mmt of the total would go toward synthesis of gas equivalent to the production of three plants, each with the capacity of 250 million standard cubic feet per day (mmcfd). The figure was derived from the NGPRP's high-development projection of demand for substitute natural gas and was modified by MUCDS's findings concerning the viability of coal gasification.

Because success of technology for the economical production of synthetic liquid fuel from coal does not appear likely until the late 1990s, high-level development does not assume the construction of a liquefaction plant

until the year 2000. Two such plants are projected. The Stanford Research Institute (1974) has estimated that one synthetic crude oil facility producing 100,000 barrels of crude per day would require 18 mmt of coal per year. That amount is more than twice the quantity that would be consumed by a synthetic natural gas plant of 250 mmcfd capacity.

One fertilizer plant is projected for southeastern Montana by the year 2000 under high-level development. The present status of technology makes development possibilities slim. The Koppers' Totzek process seems to be the most feasible conversion process at this time and would require a maximum of 3.5 mmt of coal per year to produce 2,300 tons of fertilizer per day (t/d).

The export of coal in the year 2000 under high-level development is projected to reach 368.5 mmt. This quantity was derived from the NGPRP's high-development projection plus a 40 percent increase to account for the use of slurry pipelines.

Table 12 shows the location by subbasin of the coal-based electrical generation, synthetic gas, liquefaction, and fertilizer production plants forecast under the assumptions of high-level development.

Table 13 shows coal production by subbasin during the remaining years of the century under high-level development. The production figures shown in table 11 appear in the basin-wide totals for each of the consumptive uses shown in the tables--electrical generation, gasification, production of synthetic crude oil and fertilizer--plus exports. Under the assumptions of high-level coal development in the Yellowstone Basin, exports of coal by slurry pipeline would be 20 percent of coal exports by 1980 and 40 percent by 2000 (see export column, table 13).

SUMMARY OF LEVELS OF DEVELOPMENT

A gradual rise in coal production to 1980 at least is practically inevitable based on the demand for coal represented in existing coal sales contracts. Low-level development projections reflect the existing situation plus the added demand of planned coal-for-export sales contracts. (The projected low-level demand for coal is similar to the intermediate coal development profile of the Northern Great Plains Resource Program (1974b).) High-level development is a projection of coal production based on assumptions about U.S. energy use under a policy of national self-sufficiency and a reliance on coal rather than energy conservation, alternative energy sources, oil, natural gas, and nuclear power. (An implicit assumption is that the coal would be produced in western strip mines rather than eastern underground mines.) Under high-level development, coal production tonnages could reach the totals indicated in table 14. Intermediate-level development projections represent means between the low and high levels of development. As far as we know, no one of the three development levels is more probable than the others.

Figure 3 presents a graph of coal production in the Yellowstone River Basin for the three levels of development during the remaining years of the

Table 12. Location of coal conversion facilities through the year 2000, high-level development

Subbasin	1000-mw Electric Generating Plants	250-mmcf/d Synthetic Gas Plants	100,000-b/d Synthetic Crude Plants	2300-t/d Fertilizer Plants
		1980		
Mid-Yellowstone	1	0	0	0
All others	0	0	0	0
TOTAL	1	0	0	0
		1985		
Mid-Yellowstone	2	0	0	0
All others	0	0	0	0
TOTAL	2	0	0	0
		2000		
Tongue	3	1	1	0
Mid-Yellowstone	3	2	1	0
Powder	1	0	0	0
Bighorn	1	0	0	0
Lower Yellowstone	0	0	0	1
TOTAL	8	3	2	1

Table 13. Coal tonnage location by Yellowstone River subbasins, high-level development, 1980, 1985, 2000 (mmt/y)

Subbasin	Electric Generation	Gasification	Syncrude	Fertilizer	Rail	Export Slurry	Total	Total
1980								
Tongue	0	0	0	0	32.2	0	32.2	32.2
Mid-Yellowstone	4.0	0	0	0	25.0	0	25.0	29.0
Powder	0	0	0	0	7.1	0	7.1	7.1
Bighorn	0	0	0	0	7.1	0	7.1	7.1
Lower Yellowstone	0	0	0	0	0	0	0	0
TOTAL	4.0	0	0	0	71.4	0	71.4	75.4
1985								
Tongue	0	0	0	0	71.7	17.9	89.6	89.6
Mid-Yellowstone	8.0	0	0	0	55.8	13.9	69.7	77.7
Powder	0	0	0	0	15.9	4.0	19.9	19.9
Bighorn	0	0	0	0	15.9	4.0	19.9	19.9
Lower Yellowstone	0	0	0	0	0	0	0	0
TOTAL	8.0	0	0	0	159.3	39.8	199.1	207.1
2000								
Tongue	12.0	7.6	18.0	0	99.5	66.3	165.8	203.4
Mid-Yellowstone	12.0	15.2	18.0	0	77.3	51.6	128.9	174.1
Powder	4.0	0	0	0	22.1	14.8	36.9	40.9
Bighorn	4.0	0	0	0	22.1	14.8	36.9	40.9
Lower Yellowstone	0	0	0	3.5	0	0	0	3.5
TOTAL	32.0	22.8	36.0	3.5	221.0	147.5	368.5	462.8

Table 14. Coal production for consumption under three levels of development, Yellowstone River Basin, through the year 2000 (mmt/y)

Consuming Sector	Low Level	Intermediate Level	High Level
	1971 (Actual)		
Household and Commercial	0.1	0.1	0.1
Industrial	0.1	0.1	0.1
Electrical Generation	0.8	0.8	0.8
Synthetic Fuel	0	0	0
Exports	6.1	6.1	6.1
TOTAL	7.1	7.1	7.1
	1975 (Actual)		
Household and Commercial	0.2	0.2	0.2
Industrial	0.2	0.2	0.2
Electrical Generation	0.8	0.8	0.8
Synthetic Fuel	0	0	0
Exports	21.0	21.0	21.0
TOTAL	22.2	22.2	22.2
	1980		
Household and Commercial	insig.	insig.	insig.
Industrial	insig.	insig.	insig.
Electrical Generation	4.0	4.0	4.0
Synthetic Fuel	0	0	0
Exports	66.0	68.6	71.4
TOTAL	70.0	72.6	75.4
	1985		
Household and Commercial	insig.	insig.	insig.
Industrial	insig.	insig.	insig.
Electrical Generation	4.0	8.0	8.0
Synthetic Fuel	0	0	0
Exports	114.0	154.6	199.1
TOTAL	118.0	162.6	207.1
	2000		
Household and Commercial	insig.	insig.	insig.
Industrial	insig.	insig.	insig.
Electrical Generation	8.0	24.0	32.0
Synthetic Fuel			
Gas	7.6	7.6	22.8
Crude	0	0	36.0
Fertilizer	0	0	3.5
Exports	171.1	293.2	368.5
TOTAL	186.7	324.8	462.8

Figure 3. Base, low, intermediate and high alternative futures for coal production in the Yellowstone River Basin.

century. It is obvious from the graph that the year 1980 will be a significant turning point for questions of public policy associated with coal development.

Until 1980, under all three development assumptions, only the Mid-Yellowstone Subbasin would have energy conversion facilities--the equivalent of one 1,000-mw power plant. By 1985, under intermediate or high-level development, the Mid-Yellowstone would have two 1,000-mw power plants.

Table 15 illustrates the situation by the end of the century. With low-level development, there would be a total of 2000 mw of electrical generation in the Mid-Yellowstone and Tongue Subbasins, and there would be one 250-mmcf/d synthetic gas plant in the Mid-Yellowstone. With intermediate-level development, there would be 6,000 mw of electrical generation facilities: half of it in the Mid-Yellowstone, 2,000 mw in the Tongue, and 1,000 mw in the Powder. The Mid-Yellowstone would have one synthetic gas plant.

With high-level development, the addition of a 1,000-mw power plant in the Bighorn Subbasin would bring to four the total of subbasins with energy conversion plants. The Tongue Subbasin would have yet another power plant under high-level development, for a basin total of 3,000 mw, and would contain a 250-mmcf/d synthetic gas plant and a 100,000-b/d synthetic crude oil plant as well. The Mid-Yellowstone Subbasin would have one synthetic crude oil plant and two synthetic gas plants in addition to its power plants. The Lower Yellowstone Subbasin also would enter the picture with a 2,300-t/d fertilizer plant. Four subbasins would remain unaffected by direct impacts of energy facilities under high-level development even in the year 2000; Upper Yellowstone, Billings Area, Clarks Fork Yellowstone, and Kinsey Area.

WATER USE ASSOCIATED WITH PROJECTED ENERGY DEVELOPMENT

Annual water and coal consumption requirements for the conversion plants envisioned have been calculated (see table 16). Using the water-use information in table 16 and information on the expected numbers of energy conversion facilities in each subbasin, a comprehensive picture of water use by subbasin for the years 1980, 1985, and 2000 is presented in tables 17, 18, and 19. The basin-wide totals for all uses in 1980, 1985, and 2000 are 18,770, 61,995, and 321,175 af/y, respectively, under high-level development.

Table 15. Coal Conversion in the Yellowstone Basin in 2000

Subbasin[a]	Electric Generation (mw)	SNG (mmcf/d)	Syncrude (b/d)	Fertilizer (t/d)
LOW-LEVEL DEVELOPMENT				
Bighorn	0	0	0	0
Mid-Yellowstone	1,500	250	0	0
Tongue	500	0	0	0
Powder	0	0	0	0
Lower Yellowstone	0	0	0	0
TOTAL	2,000	250	0	0
INTERMEDIATE-LEVEL DEVELOPMENT				
Bighorn	0	0	0	0
Mid-Yellowstone	3,000	250	0	0
Tongue	2,000	0	0	0
Powder	1,000	0	0	0
Lower Yellowstone	0	0	0	0
TOTAL	6,000	250	0	0
HIGH-LEVEL DEVELOPMENT				
Bighorn	1,000	0	0	0
Mid-Yellowstone	3,000	500	100,000	0
Tongue	3,000	250	100,000	0
Powder	1,000	0	0	0
Lower Yellowstone	0	0	0	2,300
TOTAL	8,000	750	200,000	2,300

[a]The four subbasins not listed (Upper Yellowstone, Billings Area, Clarks Fork Yellowstone, and Kinsey Area) are not expected to include sites for coal conversion facilities.

Table 16. Annual water and coal requirements for coal processes

Process	Water	Coal
Thermal-electric generation	15,000 af/y/1,000 mw	4 mmt/1,000 mw
Gasification	9,000 af/y/250 mmcf/d	7.6 mmt/250 mmcf/d
Syncrude	29,000 af/y/100,000 b/d	18 mmt/100,000 b/d
Fertilizer	13,000 af/y/2,300 t/d	3.5 mmt/2,300 t/d
Slurry	750 af/mmt	
Strip Mining	50 af/mmt	

Table 17. Water use in coal mining and electrical generation by 1980 by subbasin (af/y)

Subbasin[a]	Elec. Generation	Strip Mining	Total
LOW-LEVEL DEVELOPMENT			
Tongue	0	1,490	1,490
Mid-Yellowstone	15,000	1,360	16,360
Powder	0	330	330
Bighorn	0	330	330
TOTAL	15,000	3,510	18,510
INTERMEDIATE-LEVEL DEVELOPMENT			
Tongue	0	1,540	1,540
Mid-Yellowstone	15,000	1,400	16,400
Powder	0	350	350
Bighorn	0	350	350
TOTAL	15,000	3,640	18,640
HIGH-LEVEL DEVELOPMENT			
Tongue	0	1,610	1,610
Mid-Yellowstone	15,000	1,450	16,450
Powder	0	360	360
Bighorn	0	360	360
TOTAL	15,000	3,780	18,780

[a]Four subbasins (Upper Yellowstone, Billings Area, Clarks Fork Yellowstone, and Kinsey Area) are not expected to experience water depletion associated with coal development. The Lower Yellowstone Subbasin would be subject to coal development only by the year 2000.

Table 18. Water use in coal mining, transportation and conversion processes by 1985 by subbasin (af/y)

Subbasin[a]	Elec. Generation	Slurry Export[b]	Strip Mining	Total
LOW-LEVEL DEVELOPMENT				
Tongue	0	0	2,570	2,570
Mid-Yellowstone	15,000	0	2,200	17,200
Powder	0	0	570	570
Bighorn	0	0	570	570
TOTAL	15,000	0	5,910	20,910
INTERMEDIATE-LEVEL DEVELOPMENT				
Tongue	0	0	3,480	3,480
Mid-Yellowstone	30,000	0	3,110	33,110
Powder	0	0	780	780
Bighorn	0	0	780	780
TOTAL	30,000	0	8,150	38,150
HIGH-LEVEL DEVELOPMENT				
Tongue	0	6,720	4,480	11,200
Mid-Yellowstone	30,000	10,430	3,890	44,310
Powder	0	1,500	1,000	2,500
Bighorn	0	3,000	1,000	4,000
TOTAL	30,000	21,650	10,370	62,010

[a]The four subbasins not shown (Upper Yellowstone, Billings Area, Clarks Fork Yellowstone and Kinsey Area) are not expected to experience water depletion association with coal development. The Lower Yellowstone Subbasin would be subject to coal development only by the year 2000.

[b]It is assumed that half of the water for slurry in the Tongue and Powder subbasins will be from deep ground water, and half fromsurface water. In the Mid-Yellowstone and Bighorn subbasins, all water for slurry is assumed to come from surface supplies.

Table 19. Water use in coal mining, transportation and conversion processes by 2000 by subbasin (af/y)

Subbasin[a]	INCREASE IN DEPLETION Elec. Generation	Gasifi- cation	Syn- crude	Ferti- lizer	Slurry Export[b]	Strip Mining	Total
LOW-LEVEL DEVELOPMENT							
Bighorn	0	0	0	0	0	860	860
Mid-Yellowstone	22,500	9,000	0	0	0	3,680	35,180
Tongue	7,500	0	0	0	0	3,950	11,450
Powder	0	0	0	0	0	860	860
Lower Yellowstone	0	0	0	0	0	0	0
Total	30,000	9,000				9,350	48,350
INTERMEDIATE-LEVEL DEVELOPMENT							
Bighorn	0	0	0	0	4,420	1,470	5,890
Mid-Yellowstone	45,000	9,000	0	0	15,380	6,110	75,490
Tongue	30,000	0	0	0	9,900	7,000	46,900
Powder	15,000	0	0	0	2,210	1,670	18,880
Lower Yellowstone	0	0	0	0	0	0	0
Total	90,000	9,000			31,910	16,250	147,160
HIGH-LEVEL DEVELOPMENT							
Bighorn	15,000	0	0	0	11,100	2,050	28,150
Mid-Yellowstone	45,000	18,000	29,000	0	38,700	8,710	139,410
Tongue	45,000	9,000	29,000	0	24,860	10,170	118,030
Powder	15,000	0	0	0	5,550	2,050	22,600
Lower Yellowstone	0	0	0	13,000	0	0	13,000
Total	120,000	27,000	58,000	13,000	80,210	22,980	321,190

[a]The four subbasins not shown (Upper Yellowstone, Billings Area, Clarks Fork Yellowstone, and Kinsey Area), are not expected to experience water depletion associated with coal development.

[b]It is assumed that half of the water from slurry in the Tongue and Powder subbasins will be from deep ground water and half from surface water. In the Mid-Yellowstone and Bighorn subbasins, all water for slurry is assumed to come from surface supplies.

Projections of irrigated agriculture

The use of irrigated agriculture in the Yellowstone Basin has been increasing for the past few years, possibly reversing (at least temporarily) a long-term downward trend. Forecasting the extent of further expansion of irrigated agriculture to the year 2000 is complicated. General economic conditions, federal import and export policies, and world eating habits greatly affect crop prices. Many agricultural products grown in the basin through irrigation methods are used for the production of beef, which has a highly variable market. Farmer preferences and peer influences are significant but unpredictable in determining whether a farmer will decide to expand irrigation. Finally, adequate land and an accessible water supply are necessary. This study considers water and land availability and economic constraints in projecting the amount of irrigation in the Yellowstone Basin through the year 2000.

Previous studies of irrigated agriculture illustrate a range of approaches to these problems. Some of these studies forecast future development, and others analyze specific projects or geographical areas for irrigation feasibility. The OBERS Series C projections (U.S. Water Resources Council 1972) were based on estimates of anticipated supply and demand and historical trends. However, because irrigated agriculture has been declining until recently, the OBERS study predicted only small increases in Montana's irrigated acreage to meet anticipated national demand in the year 2020. It became obvious that OBERS study predictions were wrong when the projections for 2020 were surpassed in 1974. So DNRC developed new projections based on the OBERS red meat projections (Montana DNRC 1976). Neither of these studies considered the availability of suitable land or the economic limitations of irrigated agriculture. The study reported here takes these factors into account.

The Bureau of Reclamation (USBR 1955, 1959, 1963, 1971, 1972) has conducted irrigation studies in several areas of the Yellowstone Basin. Information is available for the Powder, Tongue, and Bighorn rivers, and for several projects along the mainstem of the Yellowstone. The economic analysis of these projects was updated for the Yellowstone Level B Study. A single-purpose irrigation study used in its original form (Frederiksen 1976) analyzed additional projects for inclusion in the Level B Study. Both of these studies considered large projects only and either explicitly or implicitly assumed there would be a cooperative effort to build and operate them. However, recent irrigation development in the basin has occurred primarily through private development with little or no cooperation among farmers to coordinate the installation of water-delivery systems; therefore, this study analyzes irrigation development in the Yellowstone Basin by postulating a collection of individual developments rather than cooperative projects.

METHODS

The objective of this study is to provide agricultural water-demand projections for a hydrologic model of the Yellowstone River Basin. Data were gathered and analyzed to provide general information on water demand, rather than identification of any specific development project. Three classes of information were used to identify potential water demand: 1) identification of irrigable land, 2) calculation of irrigation costs, and 3) analysis of the ability to pay these costs based on farm budgets.

IDENTIFICATION OF IRRIGABLE LAND

By systematically appraising soil, relief, and climate, parcels of land may be classified based on their suitability for irrigation. Land classification surveys made by the Water Resources Division, DNRC, were designed to investigate the theoretical potential of the land in the Yellowstone Basin to sustain irrigated farming. The term "irrigable land," as used here, denotes land with soils, topography, and drainage features appropriate for irrigation by either gravity or sprinkler methods. Such land is divided into classes on the basis of its relative potential for irrigated farming. Class 1 irrigable land has potentially high productive value; class 2 irrigable land has intermediate value, and class 3 irrigable land has the lowest suitability for irrigation among the classes. To perform the classification process for the Yellowstone River Basin, broad assumptions were necessary in areas where little soil information was available; consequently, this survey should not be considered adequate for detailed plans. Table 20 lists the classification criteria.

The land classification survey identified 2,200,000 acres of irrigable land in the basin. However, the survey considered neither water availability nor economic limitations of potential irrigation systems. For this study, water was considered to be available only from the Yellowstone River and its four main tributaries in Montana (Clarks Fork, Bighorn, Tongue, and Powder). Preliminary economic limitations were defined by using calculations from first drafts of the farm-budgets and water-delivery analyses. These preliminary calculations helped define potentially irrigable land as that no more than 3 mi from the river and no more than 450 ft above the river. Hence the total of potentially irrigable land was reduced to 440,000 acres. That land was divided into categories according to lift (50-ft increments), and pipeline length (½-mi increments) for each subbasin (table 21). Irrigation costs were calculated for each category.

CALCULATION OF IRRIGATION COSTS

In this study irrigation costs were divided into water-delivery costs and water-application costs. Water-delivery cost was defined as the total cost of pumping water from the river to the point of application. Water-application cost was defined as the cost of owning and operating a center-pivot sprinkler system.

Table 21. Irrigable acreage by lift (ft), pipeline length (mi) and subbasin in Yellowstone River Basin

Pipe Length	Lift 50	100	150	200	250	300	350	400	450	Total
				UPPER YELLOWSTONE SUBBASIN						
.5	38,076	1,014								39,090
1.0		1,404				3,962		1,601		6,967
1.5		670	1,235	3,252				1,087		6,244
2.0		2,391				1,533		2,649	3,613	10,186
2.5										0
3.0										0
Total	38,076	5,479	1,235	3,252	0	5,495	0	4,250	4,700	62,487
				CLARKS FORK YELLOWSTONE SUBBASIN						
.5	2,160	392		766		442				3,760
1.0		203								203
1.5			436			3,432		2,157		6,025
2.0			1,006							1,006
2.5					3,715					3,715
3.0						891				891
Total	2,160	595	1,442	766	3,715	4,765	0	2,157	0	15,600
				BILLINGS AREA SUBBASIN						
.5	3,308	3,324	329	2,147		222				9,330
1.0	347	71	8,084	1,305		1,254		447		11.508
1.5	110		3,549	585	442	878				5,564
2.0		165			998		278	2,325		3,766
2.5								446		446
3.0		118							662	780
Total	3,765	3,678	11,962	4,037	1,440	2,354	278	3,218	662	31,394
				BIGHORN SUBBASIN						
.5	4,478		1,309							5,787
1.0	1,608	3,451	949	1,054						7,062
1.5		2,191								2,191
2.0			1,431	783		384				2,598
2.5		1,387	581							1,968
3.0			3,734	1,159						4,893
Total	6,086	7,029	8,004	2,996	0	384	0	0	0	24,499
				MID-YELLOWSTONE SUBBASIN						
.5	16,000	1,691								17,691
1.0	3,180	4,358	4,616	2,802	297					15,253
1.5		4,004		2,270	4,522	309	2,071			13,176
2.0	820	257	2,693	6,681	3,353	1,149				14,953
2.5		428		3,534		4,851				8,813
3.0			1,979			2,459	1,538			5,976
Total	20,000	10,738	9,288	15,287	8,172	8,768	3,609	0	0	75,862
				KINSEY AREA SUBBASIN						
.5	3,248			1,180						4,428
1.0			539							539
1.5	308	2,035				731				3,074
2.0		464				546	1,405			2,415
2.5										0
3.0										0
Total	3,556	2,499	549	1,180	0	1,277	1,405	0	0	10,456
				TONGUE SUBBASIN						
.5	21,947						0			21,947
1.0										0
1.5				983	1,004					1,987
2.0										0
2.5						529				529
3.0										0
Total	21,947	0	0	983	1,004	529		0	0	24,463
				POWDER SUBBASIN						
.5	74,224									74,224
1.0	981									981
1.5					993	1,288				2,281
2.0						2,612				2,612
2.5							6,872			6,872
3.0							904	27,040		27,944
Total	75,205	0	0	0	993	3,900	7,776	27,040	0	114,914
				LOWER YELLOWSTONE SUBBASIN						
.5	23,677	1,804	1,775							27,256
1.0	1,813	4,992						4,887		11,692
1.5		2,599	792	386				12,389		16,166
2.0		805	4,807	2,120	1,603	564	537	290		10,726
2.5				350				5,101		5,451
3.0		963		355			1,341	6,563		9,222
Total	25,490	11,163	7,374	3,211	1,603	564	1,878	29,230	0	80,513

Water Delivery Costs

The cost of delivering water to the farm depends on the lift, distance, and amount of water delivered. Because of the large size of the study area and limitations of data, plans could not be tailored for individual farm sizes, irrigation layouts, and soils data. Therefore, several assumptions and generalizations were made.

A hypothetical 320 acre farm was used as the basis for all calculations. Water would be diverted at the rate of 1 cfs/50 acres (6.4 cfs/farm). Crop water requirements were met at 2.84 acre-feet/acre, including a 65 percent irrigation efficiency factor (USDA 1974). Therefore, the annual water requirement for the 320-acre farm would be 908 acre-feet. We assumed that the pumps would be electric and would require 1,717 hours of operation per year. The cost of electricity was assumed to be $.01/kWh.

Using the foregoing assumptions, a computer program was used to calculate the annual cost of delivering water to the farm. All equations and cost factors were provided by the U.S. Bureau of Reclamation (USBR), and were updated to January 1976 prices.

The initial investment for vertical pumps was determined from the equation:

$$C = (QI)(6.10TDH + 600)$$

where: C = cost of pumps ($)

Q = flow rate (6.4 cfs)

I = Cost index factor (2.09)

TDH = Total dynamic head

Total dynamic head equals static lift plus friction loss. Static lift was divided into 50-ft increments from 50 to 450 ft, and friction loss was computed using the Chezy-Manning formula with a roughness coefficient of n = 0.010.

$$\text{Friction loss} = V^2 n^2 L / 2.22R^{1.33}$$

where: V = velocity (6.4cfs/area of pipe)

n = Mannings coefficient (0.010)

L = pipe length

R = hydraulic raidus (pipe diameter/4)

The total investment in pumps, housing, electrical panels, and installation was assumed to be four times the cost of the pumps (USBR cost analyses).

The initial cost of the pipe was provided by the USBR (tables 22 and 23), and excavation costs were determined from the equation:

Excavation cost = 3 WDL/27

where: W = width (twice the pipe diameter in ft)

D = depth (6 ft plus pipe diameter)

L = pipe length

Annual investment costs were obtained by amortizing the initial investment of pumps and pipe over 10 years at 10% interest, using a capital recovery factor of 0.16275.

Annual operation costs were calculated from the equation:

$$\text{Operation cost} = (1.8Q^{.47})(TDH)^{.46}(T/168)^{.34}(1.2W_c + I_w)$$

where: Q = flow rate (6.4 cfs)

TDH = total dynamic head

T = operation time (1,717 hours)

W_c = workers wages ($5.83/hour)

I_c = costs index factor (1.87)

Maintenance costs were calculated from the equation:

$$\text{Maintenance cost} = (2Q^{.11})(TDH)^{.41}(af)^{.43}(0.49W_c + I_w)$$

where: Q = flow rate (6.4 cfs)

TDH = total dynamic head

af = water pumped (908 acre-feet/year)

W_c = workers wages ($5.83/hour)

I_w = cost index (1.87)

Finally, electricity costs were calculated from the equation:

$$C = (UQT)(TDH)/8.8E$$

where: U = electricity cost/kWh ($.01/kWh)

Q = flow rate (6.4 cfs)

T = time of operation (1,717 hours)

TDH = total dynamic head

E = pump efficiency factor (.7)

The total annual costs of operation, maintenance, and electricity were added to the amortized cost of the pumps and pipe. All calculations were repeated for each pipe size, and the most economical system was selected. Water delivery costs were then calculated for each lift and distance category, and are displayed in table 24.

Table 22. Concrete pipe costs ($/ft)

Head (ft)	Diameter (in)			
	12	18	24	30
50	8.94	14.72	21.26	28.34
100	9.27	15.26	22.89	30.52
150	9.59	16.35	23.98	32.70
200	10.79	18.53	27.25	37.06

Table 23. Steel pipe costs ($/ft)

Head (ft)	Diameter (in)						
	12	18	24	30	36	42	48
50	10.90	21.80	32.70	43.60	57.77	70.85	87.20
100	14.17	25.07	35.97	46.87	61.04	78.48	93.74
150	18.53	29.43	40.33	51.23	65.40	81.75	102.46
200	25.07	35.97	46.87	57.77	80.66	100.28	123.17
300	38.15	49.05	59.95	70.85	91.56	112.27	143.88
350	45.78	56.68	67.58	78.48	99.19	118.81	154.78
400	49.05	59.95	70.85	81.75	102.46	134.07	164.59
450	56.68	67.58	78.48	89.38	110.01	143.88	176.58

Table 24. Annual water-delivery costs ($/acre)

Length (mi)	Elevation 50	100	150	200	250	300	350	400	450
0.5	55	68	79	105	116	136	147	167	178
1.0	79	93	133	144	168	184	207	223	247
1.5	103	117	172	202	213	250	261	299	310
2.0	128	142	212	247	258	304	315	362	373
2.5	152	167	251	292	303	358	369	424	[a]
3.0	176	192	291	337	348	412	423	487	[a]

[a]Steel pipe is unsuitable for these pressures.

Water Application Costs

Water application costs were derived from information provided by Montana State University (Montana State University 1969).

Table 25 itemizes the cost of owning and operating one center-pivot sprinkler system. Changes that were made in the CES data to make the costs compatible with farm budget estimates are included under the column labeled NOTES. The initial cost of all equipment was amortized over 10 years at 10 percent interest (Capitol Recovery Factor = 0.16275) and added to the annual operating costs. The data then were indexed to December 1975 prices (Water Resources Council unpublished) to yield an annual cost of $66/acre.

Table 25. Center-pivot irrigation costs

	Costs	Notes
Initial investment	$48,022	
Annual payment	7,816	10% over 10 years
Maintenance	158	0.33% of investment
Electricity	652	65,180 kWh/yr @ 1 mill/kWh
Labor	175	$2.50/hr, 70 hrs/yr
Taxes	768	160 mills on 10% of investment
Insurance	288	.6% of investment
TOTAL per acre	9,857 66	148 irrigated acres

FARM BUDGETS AND THE ABILITY TO PAY FOR IRRIGATION

The potential for expanding irrigated land, of course, depends heavily on returns that can be expected on the investment. For each subbasin, farm budgets were prepared reflecting local cropping patterns. The budgets included the specific costs and returns associated with irrigated-crop production, plus generalized farm costs such as investment, maintenance, and repair of buildings and fences. Because the budgets included all costs associated with an irrigated farm (except water delivery and application) including payments to the farmer for his labor, management, and investment, profit after sale of the irrigated crops was assumed to be available to pay for irrigation.

Historical records (Montana Department of Agriculture 1946-74) were used to develop cropping patterns for each subbasin. All crops produced in each area were placed into one of four categories. Sugar beets represented all high-value cash crops such as beets or dry beans. Barley represented the grain crops, alfalfa represented all hay, and corn silage represented silage crops including ensiled hay and beet tops.

All calculations were based on the hypothetical 320-acre farm because data were readily available from the USBR for that size of operation. The farmstead, roads, ditches, and wasteland accounted for 18 acres (5.6 percent); the remaining 302 acres were assumed to be available for crop production. For convenience, costs and revenues were divided into four categories: fixed costs, variable costs, revenues, and perquisites.

Fixed Costs

Fixed costs included those incurred regardless of the acreage planted to a particular crop. Depreciation, repair, taxes, and investment are all fixed costs; they are listed in table 26. Depreciation was calculated on all buildings, machinery, and equipment using a 6.5 percent sinking fund factor over the expected life of the item. Repair costs were assumed to be 2 percent of the value of buildings and improvements, and 2.5 percent on machinery and equipment. A 7.1 percent return was calculated on all investments.

Taxes were assumed to be levied against 30 percent of the assessed value on land and buildings and 20 percent on machinery and equipment. The assessed value of an acre of irrigated land was assumed to be $48.00. Buildings and improvements were assumed to be assessed at 40 percent, and machinery and equipment at 50 percent of their average values. The mill levy in the Yellowstone Basin was assumed to average 160 mills.

Depreciation and repair costs for automobiles and trucks, based on mileage estimates, are shown in table 27. Fixed costs for insurance, telephone, and electricity also are included in table 27.

Table 26. Inventory of buildings, machinery and equipment; investment, repair, depreciation, and taxes for a hypothetical 320-acre farm

Item	Market Value	Annual Investment	Annual Repairs	Expected Life (yrs)	Annual Depreciation	Annual Tax
Land	$ 80,000	$ 5,680	-	-	-	$ 737
House	22,200	1,576	$444	50	$65	426
Garage	2,200	158	44	40	13	42
Granary	1,665	118	33	20	43	32
Shop	1,665	118	33	20	43	32
Fuel Tanks	444	32	9	20	12	9
Well	888	63	18	30	10	17
Plow	1,332	95	33	12	77	21
Disk	1,554	110	39	15	64	25
Harrow	355	25	7	20	9	6
Sugar Beet Equip.	7,082	503	177	12	408	113
Drill	1,554	110	39	20	40	25
Planter	1,787	127	45	15	74	26
Cultivator	1,415	100	35	12	81	23
Loader	1,132	80	28	12	65	18
Wagon	666	47	17	15	28	11
Sprayer	710	50	18	15	29	11
Baler	3,885	276	97	10	288	62
Windrow	3,996	284	100	10	296	64
Auger	699	50	17	15	29	11
Small tools	311	22	8	5	55	5
Trucks	9,435	670	[a]	[a]	[a]	151
Auto	3,885	276	[a]	[a]	[a]	62
Tractors	7,215	512	[b]	[b]	[b]	115
TOTAL		$11,082	$1,241		$1,729	$2,047

[a] Depreciation and repair costs are computed in table 27.
[b] Depreciation and repair costs are computed in table 29.

Table 27. Miscellaneous fixed costs for a hypothetical 320-acre farm

Item	Amount Used	Rate	Cost ($)
DEPRECIATION & REPAIR			
Auto	4,000 mi	$ .14/mi	560
Truck (½ T)	5,000 mi	$ .14/mi	700
Truck (2 T)	3,500 mi	$ .28/mi	980
INSURANCE			
Buildings	$32,634	$10.80/$1,000	352
Vehicles			165
TELEPHONE			90
ELECTRICITY			210
TOTAL			$3,057

Perquisites

Farmers receive certain benefits (perquisites) living on the farm. A nonfarm person usually pays the cost of owning and maintaining a house, but on a farm such items are part of the economic enterprise. The farmer--not the farm enterprise--theoretically reaps the benefit from the farm's investment in them. Table 28 lists these farm perquisites.

Technically, perquisites are items of revenue not available for capital investment; as such, they are subtracted from fixed costs.

Table 28. Farm perquisites (house, garage, well)

Item	Perquisite value ($)
Depreciation	88
Investment	1,797
Repairs	506
Taxes	486
Insurance	273
TOTAL	$3,150

Table 29. Variable costs per irrigated acre by crop

Item	Amount Used	Cost/Unit ($)	Total Cost ($)
SUGAR BEETS			
Fertilizer: N_2	100.8 lbs	0.22	22.18
P_2O5	43.3 lbs	0.16	6.93
Labor: Family	8.4 hrs	2.25	18.90
Hired	11.7 hrs	2.50	29.25
Tractor	7.1 hrs	2.78	19.74
Seed	2.5 hrs	2.78	6.95
Custom Harvest		23.31	23.31
Ensiled Tops	10.5 tons	1.30	13.65
TOTAL			140.91
CORN SILAGE			
Fertilizer: N_2	110.4 lbs	0.22	24.29
P_2O_5	59.0 lbs	0.16	9.44
Labor: Family	6.0 hrs	2.25	13.50
Hired	4.1 hrs	2.50	10.25
Tractor	3.4 hrs	2.78	9.45
Seed	0.5 bu	25.00	12.50
Silage Storage	21 tons	1.30	27.30
TOTAL			106.73
ALFALFA			
Fertilizer: N_2	0		
P_2O_5	48.0 lbs	0.16	7.68
Labor: Family	5.4 hrs	2.25	12.15
Hired	2.8 hrs	2.50	7.00
Tractor	4.1 hrs	2.78	11.40
Seed	3.0 lbs	1.86	5.58
Twine	5 tons hay	0.61	3.05
TOTAL			46.86
BARLEY			
Fertilizer: N_2	65.4 lbs	0.22	14.39
P_2O_5	38.1 lbs	0.16	6.09
Labor: Family	3.2 hrs	2.25	7.20
Hired	0		
Tractor	2.0 hrs	2.78	5.56
Seed	2.0 bu	3.70	7.40
Weed Spray		1.15	1.15
Custom Combine		7.70	7.70
TOTAL			49.49

Variable Costs

In addition to the fixed costs associated with the farm enterprise, many costs, such as fertilizer, seed, labor, and tractor use, vary with the crop type and acreage grown. Table 29 lists these variable costs per acre for a hypothetical farm. All costs were tailored to a specific crop and an anticipated yield under irrigation. Fertilizer use was based on the amount needed to produce the expected yield. Tractor costs were included as variable costs primarily because of the format of available data.

Revenues

Table 30 lists irrigated-crop production and sales per acre. Expected yields assume better-than-average management skills and reflect amounts of labor, fertilizer, and chemical sprays used to ensure good crop growth. Sales prices were based on Water Resources Council price standards (U.S. Water Resources Council 1975). Prices for silage (corn and beet tops) were based on Water Resources Council hay prices and adjusted to reflect nutrient content.

Table 30. Irrigated-crop production and sales per acre

Crop	Yield	Sales Price/Unit	Total Revenue per acre
Sugar Beets			
Beets	21 tons	$34.97	$ 734
Tops	10.5 tons	18.73	197
CROP TOTAL			931
Corn Silage	21 tons	18.73	393
Alfalfa	5 tons	44.59	223
Barley			
Grain	74 bushels	1.90	140
Straw	16 tons	2.68	43
CROP TOTAL			183

An allowance for the farmer's management skills was included in all budgets. This allowance amounted to 10 percent of the net profit, and was calculated by reducing the absolute value of all costs and profits by 10 percent. Table 31 summarizes all costs and returns and calculates the management allowance.

Table 31. Farm budget summary with management allowance

Item	$ Value	Management Allowance ($)	Net Value ($)
Investment	-11,082	1,108	-9,974
Repairs	- 1,241	124	-1,117
Depreciation	- 1,729	173	-1,556
Taxes	- 2,047	205	-1,842
Miscellaneous	- 3,057	306	-2,751
Perquisites	+ 3,150	315	+2,835
Fixed Costs & Perquisites			-14,405
Variable Costs (per acre)			
Sugar beets	-141	14	-127
Corn Silage	-107	11	- 96
Alfalfa	- 47	5	- 42
Barley	- 49	5	- 44
Variable Returns (per acre)			
Sugar beets	+931	93	+838
Corn Silage	+393	39	+354
Alfalfa	+223	22	+201
Barley	+183	18	+165

Irrigation Feasibility

The farm budgets prepared for each subbasin were based on cropping patterns listed in table 32. Variable costs and revenues were multiplied by the acres of each irrigated crop and combined with fixed costs of farming (except for the cost of water application systems) to obtain the figures shown in table 33. Then irrigation payment capacities were calculated per acre, and application-system costs (listed in table 25 as $66/acre) were subtracted from that amount to determine the landowner's capacity to pay for water-delivery systems (table 34). This per acre capacity to pay for pumping was compared with pumping costs per acre to determine the maximum pumping distance for each subbasin (table 35). Finally, the pumping distances were compared with the 440,000 acres of potentially irrigable land in the basin (table 21) to determine the total feasibly irrigable acreage. Table 36 displays the results in acres by subbasin--237,472 acres basin-wide; approximately 80 percent is within .5 mi of the water source and less than 50 feet above it.

Table 32. Cropping patterns by subbasin, 320-acre farm

Subbasin	Cropping Pattern (acres)				
	Farmstead	Grain	Hay	Silage	Cash Crop
Upper Yellowstone	18	51	239	3	9
Clarks Fork	18	51	239	3	9
Billings Area	18	88	121	24	69
Bighorn	18	79	169	9	45
Mid-Yellowstone	18	73	178	9	42
Tongue		57	196	15	33
Kinsey Area	18	54	184	24	39
Powder	18	36	217	18	30
Lower Yellowstone	18	88	115	30	69

IRRIGATION AND WATER DEPLETION

To allocate the 237,480 acres of feasibly irrigable acreage to the three development levels, we assumed that the low level of development would irrigate one-third of that figure, the intermediate level two-thirds, and the high level all 237,480 acres.

Under assumptions of this study, annual irrigation-water requirements for the feasibly irrigable acreage in each subbasin would be constant at 906 af/farm, or 3.0 af/acre assuming 302 acres under irrigation. It is further assumed that one-third of the water withdrawn for application to crops eventually finds its way back to the rivers. Hence, net water depletion from irrigation development is assumed to be 2.0 af/acre. Development is assumed to rise steadily to completion in the year 2000.

Low-level development of basin farmland--irrigating a total of one-third of the feasibly irrigable acreage in each subbasin--would deplete 158,000 af/y to water 79,160 acres (see table 37).

Intermediate-level development would irrigate a total of 158,310 acres and deplete the basin's water supply by over 316,000 af/y.

High-level development would irrigate the entire 237,480 acres of feasibly irrigable land and cause depletion of nearly 475,000 af/y.

Table 33. Costs and returns by subbasin, 320-acre farm

ubbasin	Cost $ Fixed	Variable Costs and Returns ($)								Payment Capacity ($)
		Grain		Hay		Silage		Cash Crop		
		Cost	Return	Cost	Return	Cost	Return	Cost	Return	
pper Yellowstone	14,405	2,224	8,415	10,038	48,039	288	1,062	1,143	7,542	36,960
arks Fork	14,405	2,224	8,415	10,038	48,039	288	1,062	1,143	7,542	36,960
llings Area	14,405	3,872	14,520	5,082	24,321	2,304	8,496	8,763	57,822	70,735
ghorn	14,405	3,476	13,035	7,098	33,969	864	3,186	5,815	37,710	56,562
d-Yellowstone	14,405	3,212	12,045	7,476	35,778	864	3,186	5,334	35,176	54,214
ngue	14,405	2,508	9,405	8,232	39,396	1,440	5,310	4,121	27,684	50,089
nsey Area	14,405	2,376	8,910	7,728	36,984	2,304	8,496	4,953	32,682	55,306
wder	14,405	1,584	5,940	9,114	43,617	1,728	6,372	3,810	25,140	50,476
wer Yellowstone	14,405	3,872	14,520	4,830	23,115	2,880	10,620	8,763	57,822	71,327

Table 34. Payment capacity available for pumping (per acre)

asin	Irrigation Payment Capacity	Sprinkler Cost	Payment Capacity for Pumping
pper Yellowstone	$ 122	66	$ 56
arks Fork	122	66	56
llings Area	234	66	168
ghorn	187	66	121
d-Yellowstone	182	66	116
ngue	2169	66	103
nsey Area	183	66	117
wder	167	66	101
wer Yellowstone	236	66	170

Table 35. Maximum pumping distance (mi)

ubbasin	Lift (ft)							
	50	100	150	200	250	300	350	400
pper Yellowstone	0.5							
arks Fork	0.5							
llings Area	2.5	2.5	1.0	1.0	1.0	0.5	0.5	0.5
ghorn	1.5	1.5	0.5	0.5	0.5			
d-Yellowstone	1.5	1.0	0.5	0.5	0.5			
ngue	1.5	1.0	0.5					
nsey Area	1.5	1.0	0.5	0.5	0.5			
wder	1.0	1.0	0.5					
wer Yellowstone	2.5	2.5	1.0	1.0	1.0	0.5	0.5	0.5

Table 36. Feasibly irrigable acreage by lift and pipeline length, high level of development (acres)

Pipeline length (mi)	Lift (ft) 0-50	50-100	100-150	150-200	200-250	250-300	Total
	UPPER YELLOWSTONE SUBBASIN						
0 - .5	38,076	0	0	0	0	0	38,075
	CLARKS FORK SUBBASIN						
0 - .5	2,160	0	0	0	0	0	2,160
	BILLINGS AREA SUBBASIN						
0 - .5	3,308	3,324	329	2,147	0	222	9,330
.5 - 1.0	347	71	8,084	1,305	0	0	9,807
1.0 - 1.5	110	0	0	0	0	0	110
1.5 - 2.0	0	165	0	0	0	0	165
TOTAL	3,765	3,560	8,413	3,452	0	222	19,412
	BIGHORN SUBBASIN						
0 - .5	4,478	0	1,309	0	0	0	5,787
.5 - 1.0	1,608	3,451	0	0	0	0	5,059
1.0 - 1.5	0	2,191	0	0	0	0	2,191
TOTAL	6,086	5,642	1,309	0	0	0	13,037
	MID-YELLOWSTONE SUBBASIN						
0 - .5	16,000	1,691	0	0	0	0	17,691
.5 - 1.0	3,180	4,358	0	0	0	0	7,538
TOTAL	19,180	6,049	0	0	0	0	25,229
	TONGUE SUBBASIN						
0 - .5	21,947	0	0	0	0	0	21,947
	KINSEY AREA SUBBASIN						
0 - .5	3,248	0	0	1,180	0	0	4,428
.5 - 1.0	0	0	0	0	0	0	0
1.0 - 1.5	308	0	0	0	0	0	308
TOTAL	3,556	0	0	1,180	0	0	4,736
	POWDER RIVER SUBBASIN						
0 - .5	74,224	0	0	0	0	0	74,224
.5 - 1.0	981	0	0	0	0	0	981
TOTAL	75,205	0	0	0	0	0	75,205
	LOWER YELLOWSTONE SUBBASIN						
0 - .5	23,677	1,804	1,775	0	0	0	27,256
.5 - 1.0	1,813	4,992	100	0	0	0	6,905
1.0 - 1.5	0	2,599	0	0	0	0	2,599
1.5 - 2.0	0	805	0	0	0	0	805
2.0 - 2.5	0	105	0	0	0	0	105
TOTAL	25,490	10,305	1,875	0	0	0	37,670
	BASIN SUMMARY						
0 - .5	187,118	6,819	3,413	3,327	0	222	200,899
.5 - 1.0	7,929	12,872	8,184	1,305	0	0	30,290
1.0 - 1.5	418	4,790	0	0	0	0	5,208
1.5 - 2.0	0	970	0	0	0	0	970
2.0 - 2.5	0	105	0	0	0	0	105
TOTAL	195,465	25,556	11,597	4,632	0	222	237,472

NOTE: This table should not be considered an exhaustive listing of all feasibly irrigable acreage in the Yellowstone Basin; it includes only the acreage identified as feasibly irrigable according to the geographic and economic constraints explained in this report.

Table 57. The increase in water depletion for irrigated agriculture by 2000 by subbasin

Subbasin	Acreage Increase	Increase in Depletion (af/y)
	HIGH LEVEL OF DEVELOPMENT	
Upper Yellowstone	38,080	76,160
Clarks Fork	2,160	4,320
Billings Area	19,410	38,820
Bighorn	13,040	26,080
Mid-Yellowstone	25,230	50,460
Tongue	21,950	43,900
Kinsey Area	4,740	9,480
Powder	75,200	150,400
Lower Yellowstone	37,670	75,340
TOTAL	237,480	474,960
	INTERMEDIATE LEVEL OF DEVELOPMENT	
BASIN TOTAL	158,320	316,640
	LOW LEVEL OF DEVELOPMENT	
BASIN TOTAL	79,160	158,320

NOTE: The numbers of irrigated acres at the low and intermediate levels of development are not shown by subbasin; however, those numbers are one-third and two-thirds, respectively, of the acres shown for each subbasin at the high level of development.

Projections of municipal population growth

Communities in southeastern Montana will demand more water if population increases accompany energy development. (Municipal population growth in the Yellowstone River Basin presumably would be unaffected by agricultural development, such as expanded irrigation.) The method used to project population increases due to energy development relied on the Montana Futures Process (MFP), developed by the Montana Department of Community Affairs. MFP simulates projected economic and demographic conditions. The economic calculation combines economic bases and several assumptions to simulate employment levels by industrial sectors in labor market areas (LMAS). The demographic calculation simulates population levels from a combination of the simulated labor-force participation rates.

MONTANA FUTURES PROCESS

Although MFP can be used to estimate population levels for the 14 Labor Market Areas (LMAS), it is not designed to project population changes at the municipal level. The estimated labor-market population levels therefore had to be allocated among municipalities and communities in each labor market. This allocation was made according to informed judgments concerning likely spatial development of the new population based on historical trade patterns in each labor market area.

MFP combines trends in employment and economic exports to avoid simulation of the effects of external economic changes while accounting for the region's population and employment baselines. The direct and indirect effects on employment of hypothesized developments are merged with long-term employment trends to yield simulated employment levels. These simulated employment levels are transformed into simulated population levels using employment and population multipliers assumed in the demographic calculation. The structure of the system is depicted in figure 4.

Hypothesized development → Montana I/O Model

Employment base trends → Montana I/O Model

Montana I/O Model → Simulated employment level → Demographic submodel → Simulated population level

Figure 4. Montana Futures Process simulation-model structure.

ECONOMIC CALCULATION

The economic calculation is based on employment trends of twenty-eight employment sectors (two for each LMA) at the state and LMA levels (Figure 5). The LMA data were produced by grouping county employment data from 1969 to 1973 (U.S. Department of Commerce 1975) at the LMA level. Because of the short length of this series at the LMA level, the longer 1963-74 state-level series (Montana Department of Labor and Industry 1975) was used to produce long-term projections for the LMAs.

The economic calculation relied on secondary data (U.S. Department of Commerce 1972, 1974, 1975a, 1975b) to analyze employment linkages (through an input-output model) in the state. Because this project was concerned with employment changes rather than industrial output changes, the input-output (I/O) matrix, which is usually formulated in terms of outputs, was transformed into employment terms. This transformation was based on output and employment ratios for Montana weighted by productivity projections from the Bureau of Labor Statistics (U.S. Department of Labor 1975).

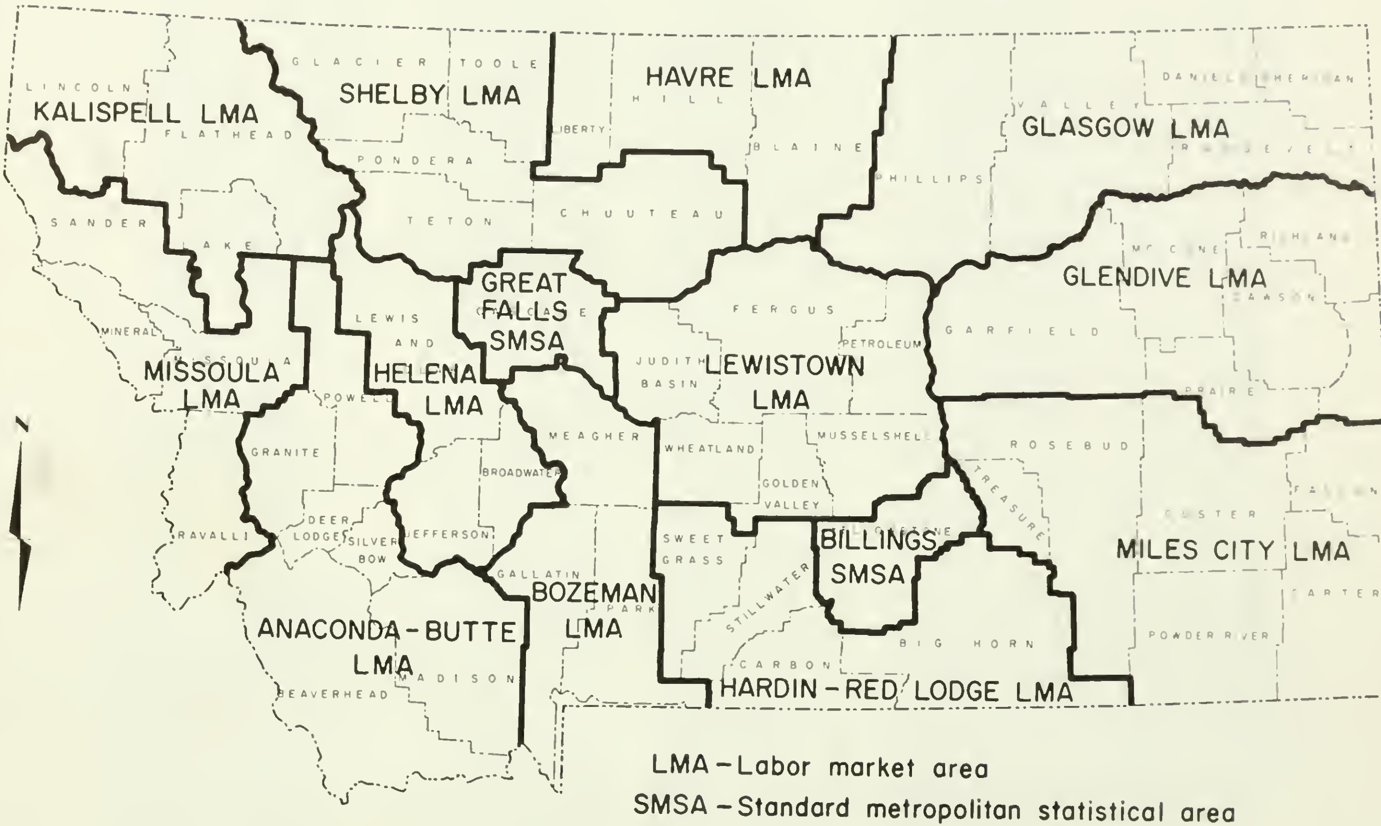
Because the I/O matrix was constructed at the state level, it was necessary to allocate state-wide employment changes associated with a specific energy development level to 14 LMAs. The allocation of secondary employment (i.e., jobs resulting from the economic impact of jobs directly related to energy development) generally was based on the change in base activity. In other words, secondary employment was allocated to the LMA where the primary employment would occur, except for financial service and trade employment, which was partially allocated to one or more LMAs by taking into account distance from marketing centers and historical trade patterns.

After the effects on employment of projected development levels were calculated and allocated to the LMAs, employment changes contingent on levels of energy development were merged with existing Montana employment trends by sector. The total employment estimations that resulted represented a simulated employment level for each LMA. Thus each simulated employment level represents the sum of existing employment trends in each LMA plus the employment changes that would be associated with levels of energy development.

DEMOGRAPHIC CALCULATION

Multiplying a simulated employment level by the commonly used employment-population multiplier produces a simulated population level. The employment-population multipliers chosen here are keyed to LMA population data and range from 2.1 to 2.4, but all converge gradually to 2.0 by the year 2000. The convergence is consistent with a 25-percent increase projected over the next 25 years in the labor-force participation rate. The overall effect of a change in the participation rate would be to dampen employment-related migration, because employment opportunities would be absorbed internally. Because of this, the population multiplier assumed to apply in the future by MFP is, in general, lower than that which exists now.

Figure 5. Labor market areas in Montana.



MUNICIPAL POPULATION

To estimate municipal water needs associated with hypothesized levels of energy development, it was necessary to allocate population increases in each LMA among affected municipalities. Because the MFP is not designed to simulate municipal population changes, additional information was required to translate LMA employment and population changes to the city level. During this study, therefore, considerable attention was given to information on the likely spatial development pattern. The pattern was then compared with the distribution of existing settlement.

Specifically, the economic activities associated with projected levels of development were disaggregated into subbasins, and we assumed that workers hired for jobs directly related to energy development would live in towns near each development area. A worker directly hired for work in any given energy development was assumed to head a household of 2.5 persons in the town closest to the energy development. The secondary population of workers generated by the primary activity was allocated among the towns of the region on the basis of past trade patterns in each basin. The total effect foreseen by the MFP for each town therefore includes the workers directly related to energy development, their families, and service sector population resulting from the new population in that town and other towns in its market area.

The data in table 38 were derived from this study's assumptions of energy-development levels and from employment information from Freudenthal et al. (1974). After the direct-worker requirements were further refined according to subbasins, these requirements were put into the MFP model. The MFP model produced the total population for the indicated municipalities under conditions of low, medium, and high energy development, and the results are shown in table 39.

INCREASED WATER USE ASSOCIATED WITH POPULATION GROWTH

Table 40 summarizes the projected population increase (from table 39) for all subbasins of the Yellowstone Basin for 1985 and 2000 and lists the resulting increases in water depletion under three levels of energy development.

Table 38. Permanent, direct energy-related employees in the Yellowstone Basin, 1985 and 2000

Subbasin	1985			2000		
	Mining	Conversion	Transportation	Mining	Conversion	Transportation
TONGUE						
Low	972	0	164	1687	0	283
Intermediate	1544	0	120	2087	360	346
High	2060	0	238	5148	2890	523
ROSEBUD						
Low	778	180	109	1298	1210	165
Intermediate	1200	360	158	2688	1390	320
High	1600	360	188	4000	3740	280
POWDER						
Low	220	0	21	411	0	69
Intermediate	343	0	58	757	180	101
High	458	0	55	1140	180	154
BIGHORN						
Low	220	0	21	411	0	69
Intermediate	343	0	58	757	0	124
High	458	0	55	1140	180	161

Table 39. Population simulations for low, medium and high energy development

	1970[a]	1985			2000		
		Low	Medium	High	Low	Medium	High
Ashland	531	847	986	2,127	2,377	5,625	7,236
Billings	63,729	79,472	79,872	80,197	94,999	95,533	98,275
Birney	13	91	129	129	60	70	137
Broadus	799	1,568	1,988	3,158	4,138	6,096	10,662
Busby	300	831	877	1,011	1,160	1,038	2,036
Colstrip	200	2,231	3,606	4,455	5,044	9,824	15,107
Forsyth	1,873	3,372	4,195	4,640	5,189	5,664	10,267
Glendive	6,441	7,168	7,168	7,168	8,341	8,341	8,712
Hardin	2,733	4,016	4,377	5,977	4,703	5,450	7,066
Lame Deer	650	934	944	2,337	1,067	1,017	1,442
Lodge Grass	806	885	939	977	1,090	1,235	1,667
Miles City	9,023	11,596	12,100	12,959	15,090	16,344	20,236
Sidney	4,551	5,120	5,120	5,120	6,031	6,037	6,208

[a]Baseline populations for Billings, Sidney, and Glendive are based on 1975 estimates.

Table 40. Population increases and water depletion[a] increases from municipal water use in the Yellowstone River Basin in 1985 and 2000

Level of Development	Population Increase	Increase in Depletion (af/y)
	1985	
Low	26,482	2,970
Intermediate	30,652	3,430
High	38,602	4,320
	2000	
Low	56,860	5,880
Intermediate	62,940	6,960
High	94,150	10,620

[a]Depletion is assumed to be 100 gal per person rounded to the nearest 10 acre-feet.

Summary

The preceding sections present assumptions and methods used to estimate water requirements in the Yellowstone River Basin to meet the demands of energy development, irrigation, and municipal growth during the remaining years of the century. Three levels of development were considered.

Table 41 summarizes the water demands arising from the activities assumed for each level of development by the year 2000. Table 42 itemizes the energy-development activities and associated water demands that appear in table 41. Appendix A details the demands of energy, irrigation, and municipal growth month by month that year in each of the subbasins.

The projections shown in table 41 are the first step in estimating the impact of potential development on the Yellowstone Basin. Part II of this report contains the second step--calculation of how the streamflow in the basin would be affected by such development. In turn, these streamflow calculations helped define the physical, biological, and economic effects of water consumption in the Yellowstone River Basin contained in the other reports of this series.

Table 41. Water requirements by demand source in the Yellowstone Basin in 2000

Level of development	Irrigation		Municipal		Energy[a]	Total Increase in Depletion[b] (af/y)
	Acreage Increase	Associated Depletion (af/y)	Population Increase	Associated Depletion (af/y)	Associated Depletion (af/y)	
Low	79,160	158,320	56,860	5,880	48,350	212,550
Intermediate	158,320	316,640	62,940	6,960	147.160	470,760
High	237.480	474,960	94,150	10,620	321.190	806,770

[a]Details of water requirements for energy use are in table 42.

[b]This total assumes that the same level of development occurs in all categories of consumption.

Table 42. Increased water requirements for coal development in the Yellowstone Basin in 2000

Level of Development	Coal Development Activity						Total
	Electric Generation	Gasification	Syncrude	Fertilizer	Export	Strip Mining	
COAL MINED (mmt/y)							
Low	8.0	7.6	0.0	0.0	171.1		186.7
Intermediate	24.0	7.6	0.0	0.0	293.2		324.8
High	32.0	22.8	36.0	3.5	368.5		462.8
CONVERSION PRODUCTION							
Low	2000 mw	250 mmcfd	0 b/d	0 t/d			
Intermediate	6000 mw	250 mmcfd	0 b/d	0 t/d			
High	8000 mw	750 mmcfd	200,000 b/d	2300 t/d			
WATER CONSUMPTION (af/y)							
Low	30,000	9,000	0	0	*	9,350	48,350
Intermediate	90,000	9,000	0	0	31,910	16,250	147,160
High	120,000	27,000	58,000	13,000	80,210	22,980	321,190

*No water consumption is shown for export under the low level of development because, for that development level, it is assumed that all export is by rail, rather than by slurry pipeline.

Part 2

Hydrologic modeling

by

Satish Nayak

Selection of a water model

MODEL VARIETIES

Although many different types of water models have been proposed and used for water planning purposes over the past decade, these models have been classified for the purposes of the Yellowstone Impact Study into two categories: optimizing (or economic) models and watershed models.

Optimizing models assume that the analyst is interested in finding the optimal solution providing lowest possible cost or maximum possible profit under a given set of constraints. These constaints may include water requirements, minimum flows, financial restraints, and other special considerations. These models are primarily meant for economic studies determining the operating policy for a system of reservoirs, new dam sites from a given set of potential sites for future demands, the allocation of water among several competitive users based on return or cost, or combinations of these. The Yellowstone Impact Study did not consider optimizing models for two reasons. First, the study did not address itself to such economic problems. Second, these models consider surface waters only and the study needed a model that could model the entire hydrologic characteristics of a basin.

Watershed models, on the other hand, attempt to model the hydrologic characteristics of a basin by defining the relationships among the principal components of the hydrologic system, for example, precipitation, snow, temperature, snowmelt, runoff, evapotranspiration, percolation, and ground water. The following five watershed models were examined for use in the study:

1) The Utah State Model;
2) Streamflow Synthesis and Reservoir Regulation (SSARR);
3) HYD-2;
4) SIMLYD-II; and
5) The State Water Planning Model (SWP).

THE UTAH STATE MODEL

The Utah State Model (Utah State University, 1973) emphasizes water quality. This model is divided into two parts: the hydrologic system and the salinity system. The hydrologic system includes programs which model precipitation (including snow), surface inflow and outflow, ground-water inflow and outflow, and evapotranspiration determined through soil moisture. The salinity system consists mainly of the soil-salt system with its interaction with diversion, surface flow and ground-water flow. The Utah State Model requires the following data:

1) inflow and outflow;
2) precipitation, including snowfall;
3) temperature;

4) reservoir;
5) soil type with water holding capacity;
6) crop for finding potential evapotranspiration;
7) diversion;
8) salt concentration of ground-water and of reservoir water; and
9) soil chemistry for water quality.

This hybrid model uses an analogue computer to analyze complex relationships and a digital computer to calculate mass balance and salinity. Calibration is achieved by adjusting the parameters of the equations iteratively until the smallest value is reached for the objective function which is $\Sigma(\text{Diff})^2$ where Diff equals the measured outflow minus the predicted outflow.

Because of its hybrid computational procedure and main emphasis on water quality, the Utah State Model was not selected for the Yellowstone Impact Study and so it is difficult to say how involved data gathering might have been. Based on the experience of the SWP model and its similarity with the Utah State Model, it appears that the data preparation would be a long process. Calibration seems to be difficult since the model must predict not only outflow but also salt concentration.

The Utah State Model, which will handle two years of data on a monthly basis for one river basin, appears to be useful in determining how different water management practices (for example, irrigation policies, cropping pattern, leaching) will affect water quality downstream.

STREAMFLOW SYNTHESIS AND RESERVOIR REGULATION (SSARR)

The SSARR, developed by the U.S. Army Corps of Engineers, North Pacific, Portland, Oregon, is a good model for determining the daily operation of a system of reservoirs and for forecasting floods and flows. The characteristics of the SSARR model include a surface-water system, a snow system, a soil moisture system, a ground-water system, and flood routing. These characteristics are very broad and a detailed description of them can be found in Program Description and User Manual for SSARR Streamflow Synthesis and Reservoir Regulation (U.S. Army Corps of Engineers 1972).

The SSARR requires massive amounts of data taken daily and even hourly. The time increments can be as small as 0.1 hour in the case of flood routing. Many of the data that this model requires would be available only if special studies were conducted to collect them. In a broad sense, the following types of data are needed:

1) inflow and outflow;
2) precipitation including snow;
3) temperature;
4) reservoir storage including area-capacity curves; and
5) tables for parameters such as soil moisture index against percentage of runoff, precipitation against evaporation reduction factor, percentage of season runoff against percentage of snow-covered area, and many more. The detailed list can be found in the SSARR manual.

The SSARR is calibrated by a trial-and-error method that appears to be a long and difficult process since there are many interacting empirical parameters needing adjustment as more data become available. Although this model can predict daily flows, the Yellowstone Impact Study requires analyses over longer periods, and so the SSARR model was not selected.

HYD-2

Program HYD-2, a generalized hydrologic model of a river system that can analyze up to fifteen stream-flow control points, is essentially an accounting model needing no calibration (USDI 1974). At each control point, some or all of which may be reservoirs, a mass balance is carried out and all losses or gains are accounted for. Although this program models only the surface water system, gains and losses due to ground-water activities are a part of the model. This model requires the following data:

1) inflow and outflow;
2) demand at each control point;
3) reservoir storage with area-capacity curves;
4) pan evaporation coefficients at each reservoir site; and
5) losses or gains at each control point due to ground-water activity in the area.

Since the main data requirements are the inflow and outflow values and estimated ground-water activity at each control point, the data preparation is less complicated than for the Utah State, the SSARR, or the SWP. This model can simulate the monthly yield of a subbasin for fifty years but cannot be used for water-quality calculations. HYD-2 was developed by the U.S. Bureau of Reclamation (USDI 1974).

SIMYLD-II

SIMYLD-II (Texas Water Development Board 1972) is based on the concept that a physical water resource system can be transformed into a capacitated network flow problem. Essentially an accounting model, since the mass balance equation must be satisfied at each control point, SIMYLD-II needs no calibration and has optimization built into it. This model's data requirements are similar to those of HYD-2 and are as follows:

1) inflow and outflow;
2) reservoir storage with area-capacity curves;
3) demand or diversion at each model point;
4) pan evaporation coefficients at each reservoir site;
5) priorities for meeting the demands; and
6) operating rules for the reservoirs.

SIMYLD-II is used primarily for two purposes: first, to simulate the least costly operation of a system subject to a specified sequence of demand and hydrology; and second, to find the yield of a subbasin or reservoir within a basin. SIMYLD-II does not have the capability for water-quality calculations. This model, designed to simulate the operation of more than

one reservoir in a system, assigns to each reservoir a priority that is converted to a cost in order to find the optimal solution.

THE STATE WATER PLANNING MODEL

The State Water Planning Model (SWP) (Montana University Joint Montana Resources Council 1972), a watershed model which can closely simulate the hydrology of a river basin, includes four major subsystems: a surface water system dealing with aspects such as precipitation, runoff, inflow, and reservoirs; a snow system dealing with snowfall, snowmelt, and sublimation losses; a ground-water system simulating ground-water activities such as deep percolation, ground-water storage, and ground-water outflow; and a soil-water system dealing with soil moisture and evapotranspiration losses. This model has been modified to include water quality calculations in total dissolved solids (TDS).

The SWP requires extensive data preparation including:

(a) inflow and outflow;
(b) precipitation including snowfall;
(c) temperature including frost data;
(d) pan evaporation coefficients at each reservoir site;
(e) soil type with water holding capacity;
(f) crop data for finding consumptive use and potential evapotranspiration;
(g) diversion data; and
(h) regression equations for TDS calculations.

All relationships among the elements of the model are expressed as a system of linear equations that represent the basin characteristics and are obtained from knowledge about the area and the relationships described in hydrologic literature. Calibration criteria are based on a zero trend in the available ground-water capacity. Calibration is accomplished by running the program iteratively and changing some of the relationships in the system of equations.

This model can be used to determine the yield of a basin under a given operating policy. Although SWP is not meant to provide information for controlling or correcting the water quality of the outflow, water quality calculations can be made on the outflow.

MODEL COMPARISON

Although the Utah State Model and the SSARR programs were not used, preliminary evaluation of these programs showed that they would not meet the requirements of the study. The Utah State Model was eliminated mainly for its hybrid computational procedure and its narrow emphasis on water quality, although other factors indicated that it would be unsatisfactory. This study required a model that could simulate much longer periods than the twenty-four months that the Utah State Model could simulate. Also, the Utah State Model's data preparation and model calibration appeared to be a longer and more difficult process than that in other models that could provide information more useful to the study. The SSARR was eliminated because of its narrow

range simulating the day-to-day operation of a system of reservoirs, and because it requires massive amounts of data that have not been collected.

The HYD-2, SIMYLD-II, and SWP programs were all run for detailed evaluation and comparison. The results of the evaluation and comparison may be found in table 43 and the criteria used to evaluate the models are listed in table 44.

When the comparison was made, it was apparent that SIMLYD-II has all the capabilities that HYD-2 has plus additional capabilities and therefore HYD-2 was dropped from consideration. The SWP and the SIMLYD-II programs were both good models for the study, but the SWP was more complete than SIMYLD-II. Also, the SWP had water quality abilities that SIMYLD-II lacked. And using the SWP had another advantage: since the program was developed under a grant from the Water Resources Division of DNRC to the Water Resources Research Center at Montana State University, Bozeman, Montana, experts who worked on that project would be available for any necessary modification of the SWP program. Therefore, the State Water Plan (SWP) was selected for the Yellowstone Impact Study and applied to the Yellowstone Basin.

Table 43. Model comparison

	State Water Plan	HYD-2	SIMYLD-II
Type of Model	A hydrologic model using a system of equations defining the interaction of ground-water, surface water, snowmelt, and other subsystems.	An accounting model mainly simulating surface waters.	An accounting mod mainly simulating surface waters.
	Only one reservoir per basin may be simulated.	More than one reservoir per basin may be simulated.	More than one reservoir per bas may be simulated.
	Simulation, in a limited sense, can be carried out for basins without a reservoir.	Simulation, in a limited sense, can be carried out for basins without a reservoir.	Simulation cannot be carried out if shortages occur.
	No optimization.	No optimization.	Optimization is possible.
Data[a]	Temperature dependent data are required.	No temperature dependent data are required.	No temperature dependent data are required.
	Soil moisture data are required.	No soil moisture data are required.	No soil moisture data are required.
Calibration	Lengthy calibration is required. Computer time for each calibration run approximately equals that for a simulation run.	No calibration is needed.	No calibration is needed.
Simulation	All three models may be used for finding the yield of a basin. The operating criteria are less rigid and limited for the SIMYLD-II model than for the SWP or HYD-2 models.		

Table 43 Continued.

	State Water Plan	HYD-2	SIMYLD-II
Computer time	Presently, each computer run costs approximately $30.00 for 360 months.	Presently, each computer run costs approximately $6.00 for 360 months.	Presently, each computer run costs approximately $12.00 to $14.00 for 360 months.
Learning time	SWP is not an "off-the-shelf" model. A good understanding of the subsystems and their interrelationships is required. A knowledge of matrix inversion is desirable.	HYD-2 is an "off-the-shelf" model of the accounting variety.	SIMYLD-II is an "off-the-shelf" model of the accounting variet The optimization method requires an understanding of network flow theory.
Water quality	Water quality is calculated but not directly controlled.	No provision for water quality.	No provision for water quality.

[a]Data requirements and preparations are more complex and time consuming for SWP than for HYD-2 or SIMYLD-II. Monthly data is acceptable to SWP up to 360 months and HYD-2 and SIMYLD-II up to 600 months.

Table 44. Suggested model evaluation criteria

1. Validity of results.
2. Ease of verification.
3. Ease of learning and use.
4. Cost/benefit.
5. Data requirements.
6. Ease of modifying to simulate different situations (flexibility).
7. Smallest time increment which can be used.
8. Accounts for known physical, hydrologic relationships.
9. Assumptions required and their validity.
10. Economics built in (optimizing).
11. Subbasin interaction capability.
12. Calibration effort required.
13. Sophistication of output.
14. Ease of debugging problems.
15. Outputs available in addition to yields and flows.
16. Prediction capability.
17. Existing documentation.
18. Routing capability.
19. Water quality.
20. Physical availability to other users.

Adaptation of the SWP

HOW THE SWP MODEL WAS USED

The SWP was modified to include water quality calculations and to make the program ready to use in each subbasin with a minimum of changes. Because watershed models must be tailored to each subbasin, the program was divided into two sections, one that included subroutines independent of the subbasin under study and another containing subroutines dependent on that subbasin. By limiting the amount of reprogramming of the model necessary for each subbasin, considerable time and money was saved. The revised program includes many new subroutines.

The model consists of sixteen linear equations that describe the interrelationship of the four major subsystems: including a surface water system, a snow system, a ground-water system, and a soil water system. Each equation represents a secondary datum whose value is obtained during the calibration phase of the modeling. The primary input of the equations consists of inflow, outflow, precipitation, reservoir storage, and temperature. The system of linear equations is solved for each month of the study period, keeping a link from one month to the next, especially in variables dealing with storage.

Despite the program changes and the inclusion of water quality calculations, the program's variable names, formats, and basic character remained essentially the same as the program developed by Boyd and Williams (Montana University 1972).

The water quality subroutine, added to meet the requirement of the Yellowstone Impact Study for water quality calculations, can take twelve monthly regression equations for total dissolved solids (TDS) based on flows. The subroutine calculates the TDS for the incoming flow as well as the outgoing flow and has provisions for two levels of salt pickup by return flows. A brief description of procedure used with the SWP follows.

CALIBRATION

Calibration of all subbasins was based on data (see "Data Preparation," below) covering the 360 monthly time increments from 1944 through 1973.

Calibration begins by using a simple program to calculate the initial coefficients of the model. These initial coefficients are then used in an annual version of the SWP model that is then run with the data covering the thirty individual years. The initial coefficients are adjusted and the model is reiterated two or three times until final values for the annual model's coefficients are reached.

The annual model (which becomes the monthly model with the reduction in scale of some factors and the addition of systems simulating such details as

snow pack and soil moisture) also acts as a basis for assigning certain coefficients. The monthly model is calibrated by running data covering the 360 months using the annual model's coefficients and adjusting them until the model is consistent with the data. The calibration of the monthly model requires more runs and adjustments of the coefficients of the annual model since the monthly model uses 360 months of data and considers twice as many variables. In addition, although the model uses the relationships between monthly average temperature and variables such as snowmelt, potential evapotranspiration, and soil moisture, the responses of these variables are more dependent upon maximum and minimum temperatures; therefore, determining the final coefficients for the monthly model requires some subjective judgment.

The monthly model used in this study differs slightly from the original SWP model. The subsystems for ice formation and irrigation diversion deviation were eliminated to reduce the size of the model's matrix. The subsystems for subsurface outflow, subsurface inflow, and snowfall were treated outside the system of equations, another step to reduce the matrix size.

SIMULATIONS

After the model had been calibrated for a particular subbasin, it was ready for simulations. Scenarios describing low, intermediate, and high water use (which are explained in Part 1 of this report) were run for each subbasin. The model can perform simulations of the following situations and policies:

1) Keeping a reservoir as full as possible, making releases only when required to augment flows and releasing excess flows only when the reservoir is full.

2) Keeping a reservoir as full as possible making releases to augment irrigation flows (when the reservoir inflow is less than the irrigation flow) plus a minimum required flow such as the Department of Fish, Wildlife and Parks would request; and

3) A system that has no reservoirs and so has no capacity to augment or regulate flows except through additional diversion.

DATA PREPARATION

Inflow and outflow data for all subbasins were obtained from computer files (USDI) and Water Supply Papers provided by the USGS. Precipitation and temperature data were obtained from the SWP model data bank (Montana University) and the U.S. Climatological Records. Montana Agricultural Statistics (Montana Department of Agriculture 1946-74) provided crop data for determining the potential evapotranspiration on a monthly basis for all subbasins. Root zone capacity was calculated from the soils maps provided by the Soil Conservation Service. Bureau of Reclamation data on diversion projects in the Yellowstone Basin were used to estimate the diversion requirements for most of the subbasins on the mainstem. A brief description of the procedure used in preparing the data follows.

Priority

The largest use of water in the Yellowstone Basin is for agriculture, including irrigated farming, dryland farming, and ranching. Municipal and industrial water uses, though important, are relatively small, at present, compared to agricultural water use. With recent attention on the coal development and thermal energy production potential in the southeastern part of Montana, the water demand for energy has become significant. In this study, water for energy was treated as an industrial demand. Municipal and agricultural demands were given priority over energy demand for all simulation studies.

Exports and Imports

It is assumed that all diversions from the stream are meant for use in that subbasin; however, there are situations calling for diverted water to be used in a neighboring subbasin. In such cases, this water is treated as an export in one subbasin and an import in the receiving subbasin. In most cases, diversion will be all along the length of the river, but, for the model, diversions are summed to give the net diversion for the subbasin. Actual diversion data from projects in the basin were used as the basis for calculating total diversion in that basin. If the data were not complete, an average value was used in place of the missing data or period. In basins where the diversion data were incomplete or nonexistent, like the Powder River Basin, the diversion data were created by using consumptive use requirement, area, precipitation, and the irrigation practice used. The total irrigated acreage for different subbasins was obtained from irrigated cropland harvested data found in Montana Agricultural Statistics (Montana Department of Agriculture 1946-74).

Streamflow. Inflow and outflow data for each subbasin were obtained from the gaging stations nearest to the subbasin boundary. In some cases the gaging stations were either deep inside or outside the drainage boundaries. In such situations, flows were estimated from the proportions of the drainage area, a regression equation, or both, or from some relevant information that can be used in predicting flows. Each basin was treated differently depending on availability of information.

Precipitation. To obtain the average precipitation for the area under consideration, all weather stations with thirty years of records were considered. If the station had a few missing observations, they were synthesized by using regression analysis or by averaging. In a few cases, where the stations were not uniformly spaced or did not cover the entire area, the Thiessen polygon method was used. In these cases, mean precipitation was calculated by using the following expression:

$$P_m = \sum \frac{A_i P_i}{A_i}$$

where: P_m = mean precipitation for the subbasin in inches

P_i = precipitation of the i^{th} measuring station in inches

A_i = area corresponding to the i^{th} measuring station in acres

If the gaging stations were all uniformly spread over the area, then:

$$P_m = \frac{\Sigma P_i}{n}$$

where: P_m = average precipitation for the subbasin in inches

P_i = precipitation of the i^{th} measuring station in inches

n = total number of measuring stations

Temperature. Temperature data were treated exactly the same way as precipitation data. All weather stations with adequate records were used in calculating the mean value. Missing data or values were created using an appropriate method. The Thiessen polygon method for finding average temperature was used whenever appropriate:

$$T_m = \sum \frac{A_i T_i}{A_i}$$

where: T_m = average temperature for the subbasin in Fahrenheit degrees

T_i = temperature at the i^{th} measuring station in Fahrenheit degrees

A_i = area corresponding to the i^{th} measuring station in acres

The following equation was used to obtain the average value of the temperature in cases where the measuring stations were uniformly spaced over the basin:

$$T_m = \frac{\Sigma T_i}{n}$$

where: T_m = average temperature for the subbasin in Fahrenheit degrees

T_i = temperature at the i^{th} measuring station in Fahrenheit degrees

n = total number of measuring stations.

Reservoir Storage. Reservoir storage was considered only if storage could be used as a regulating device for the flows. In subbasins having more than one reservoir, the reservoirs were lumped to give the net storage capacity of the basin. Channel storage was not considered because it could not be used for regulation of flows.

Root Zone Capacity. A wide range of soil types exists within the root zone of the drainage area. Each of these soil types exhibits a different

capacity for holding percolating waters. This information was used to determine the field capacity of the subbasin (i.e. the area weighted average of soil moisture holding capacity) using the following equation:

$$FC = \sum A_i C_i$$

where: FC = field capacity of the subbasin in million acre-feet

A_i = area in million acres per soil type

C_i = root zone capacity in feet for A_i

Potential Evapotranspiration. Potential evapotranspiration values were determined on a monthly basis for individual vegetative types. For agricultural crops, the Modified Blaney Criddle method (USDA 1970) was used and for native vegetation the Thornthwaite method (USDA 1970) was applied. These quantities were added together to provide the net potential evapotranspiration for each basin by month. The crop acreage data were obtained from Montana Agricultural Statistics (Montana Department of Agriculture 1946-74).

THE ANNUAL AND MONTHLY MODELS

ANNUAL MODEL

Definition of the model began with determining the relationships between the variables. Since the study used the SWP model, the study model used the same nomenclature and relationships as the original SWP. Definitions of the annual model's variables (expressed in million acre-feet) follow:

X1 = Surface outflow
X2 = Surface inflow
X3 = Initial storage
X4 = Terminal storage
X5 = Precipitation
X6 = Surface loss or the consumptive use
X7 = Subsurface outflow
X8 = Subsurface inflow
X9 = Initial available capacity
X10 = Terminal available capacity
X11 = Percolation
X12 = Subsurface discharge

The following equations defined the model's relationships:

1) Surface loss: $X6 = -X1 + X2 + X3 - X4 + X5 - X11 + X12$

2) Subsurface outflow: $X7 = C1 + (K3)(X1)$

3) Subsurface inflow: $X8 = C2 + (K4)(X2)$

4) Terminal available capacity: $X10 = X7 - X8 + X9 - X11 + X12$

5) Percolation: $X11 = SF\,(K7)(X2) + K8(X3+X4) + (K10)(X12) + X5$

6) Subsurface Discharge: $X12 = C4 - C3(X9 + X10)$

7) Assumptions: $\overline{X8} = (K2)(\overline{X7})$

$\overline{X}_7 + \overline{X}_8 = K1\,(\overline{X1} + \overline{X2})$

$(K6)(\overline{X12}) = C4$

$\overline{X9} = \overline{X10}$

$\overline{X9} = \overline{X5} + \overline{X2}\ (A_s/A_b)$

where: $\overline{X2}$ = average inflow into Montana's portion of the Yellowstone Basin[1]

A_s = area of the subbasin in acres

A_b = area of Montana's portion of the Yellowstone Basin in acres

SF = scale factor

Initial Coefficients (C and K Values)

Choosing the model's initial coefficients (K values) is the most difficult part of this procedure and requires subjective judgment based on a thorough knowledge of the hydrology of the basin. Once these K values had been selected, they were read into a simple program using thirty-year average values of X1, X2, X3, X4, and X5 for the basin. The output of this program consisted of initial coefficients for the annual version of the model (C1, C2, C3, C4) and the initial values of X9 and SF. These C values, in turn, were used to run an annual version of the model using data from each of the thirty years. Each time a run was made, the C values were adjusted so that $\overline{X9} = \overline{X10}$ which implies that during the thirty-year period, the ground-water storage is neither built up nor depleted. Once the condition of zero trend was achieved, the C values had been adjusted until they became the values of the annual model's coefficients. The coefficients of the monthly model could then be developed from the coefficients of the annual model through a similar though more complex process.

Table 45 shows the values of K1 through K10 used for each of the nine subbasins as well as the final values of C1, C2, C3, C4, and SF. In addition to these values, the initial value of $\overline{X9}$, the average value of $\overline{X10}$ and the sum of all $\overline{X6}$ are listed in the same table.

[1] A bar above the variable X's indicates an average value.

Table 45. Model Coefficients

Coefficient	Upper Yellowstone	Clarks Fork	Billings Area	Bighorn	Mid-Yellowstone	Tongue	Kinsey Area	Powder	Lower Yellowstone
K1	.050	.040	.030	.040	.030	.030	.008	.030	.020
K2	.960	.960	.970	.965	.970	.970	.960	.980	.960
K3	.015	.015	.015	.020	.015	.015	.006	.015	.010
K4	.015	.015	.015	.020	.015	.015	.006	.015	.010
K5	.050	.060	.060		.060	.060	.020	.060	.020
K6	2.000	2.000	2.00	2.000	2.000	2.000	1.250	2.000	1.250
K7	1.000	1.000	1.00	1.000	1.000	1.000	.500	1.000	.500
K8	.200	.200	.250	.250	.250	.250	.250	.250	.250
K9	1.000	1.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
K10	.500	.500	.500	.500	.500	.500	.500	.500	.500
Area in M Acres	3.805440	1.001376		2.266788		2.463360	.933812	2.51090	3.980582
C1	.106151	.019017	.079541	.056322	.122501	.005217	.018502	.005478	.95738
C2	.131857	.021086	.071450	.054806	.115654	.005004	.016296	.006587	.087535
C3	.011646	.010041	.068000	.033500	.069932	.003042	.017350	.003684	.004054
C4	.448829	.109762	.590000	.397499	.954247	.061278	.218811	.053674	.228189
SF	.020880	.176100	.034300	.026370	.035561	.003572	.027458	.004255	.013678
x9 Initial	9.606533	2.677895	2.020000	2.788641	3.033000	3.382400	1.201977	3.624976	5.550416
$\overline{x}$10	9.634332	2.734140	2.167467	2.968178	3.411503	3.392497	1.279755	3.639492	5.625278
Sum of all X6	193.982705	67.403834	78.002623	66.565216	N.A.	82.419387	27.323242	87.031952	139.858505

MONTHLY MODEL

The monthly model was derived from the annual model by adding more structure. For example, an annual model, having no temperature-dependent variables, treats evaporation losses from the reservoir or from streams or from vegetation as a single loss. The monthly model, however, attempts to separate these losses into different components such as evapotranspiration, evaporation from reservoirs, and the losses from the stream surface, thus accounting for seasonal temperature variation. The precipitation, for example, is assumed to be snowfall or rainfall depending upon the temperature.

The monthly model was composed of the following five subsystems:

1) SS1: Stream-Reservoir
2) SS2: Snow
3) SS3: Runoff
4) SS4: Ground Water
5) SS5: Soil Water

These five subsystems require the following fifteen parameters, expressed in million acre-feet:

1) SS1 Parameters.

X1 = stream outflow
X2 = stream inflow
X3 = initial reservoir storage
X4 = terminal reservoir storage
X6 = stream-reservoir evaporation loss

2) SS2 Parameters.

X14 = sublimation
X15 = initial snow storage
X16 = terminal snow storage

3) SS3 Parameters.

X5 = precipitation
X20 = runoff evaporation loss
X27 = irrigation import

4) SS4 Parameters.

X7 = ground-water outflow
X8 = ground-water inflow
X9 = initial ground-water capacity
X10 = terminal ground-water capacity

5) SS5 Parameters.

X23 = initial soil-water storage
X24 = terminal soil-water storage
X25 = evapotranspiration loss

6) SS1-2 (Stream-Reservoir-Snow) Parameters.

X18 = ice formation
X31 = irregular ice formation ($X31 < 0$, $T \leq 32^{0}$)

7) SS2-1 (Snow-Stream-Reservoir) Parameter.

X31 = irregular snowmelt ($X31 > 0$, $T \leq 32^{0}$)

8) SS1-3 (Stream-Reservoir-Runoff) Parameter.

X28 = irrigation diversion

9) SS3-1 (Runoff-Stream-Reservoir) Parameters.

X19 = ground-water runoff plus irrigation runoff
X31 = precipitation runoff ($T > 32^{0}$)

10) SS1-4 (Stream-Reservoir-Ground Water) Parameter.

X11 = stream-reservoir percolation

11) SS2-3 (Snow-Runoff) Parameters.

X17 = snowmelt
X22 = irregular snowmelt ($X22 < 0$, $T \leq 32^{0}$)

12) SS3-2 (Runoff-Snow) Parameters.

X13 = snowfall
X22 = irregular ice formation ($X22 > 0$, $T \leq 32^{0}$)

13) SS3-5 (Runoff-Soil Water) Parameters.

X21 = ground-water infiltration plus irrigation infiltration
X22 = precipitation infiltration ($T > 32^{0}$)

14) SS4-3 (Ground Water-Runoff) Parameter.

X12 = ground-water discharge

15) SS5-4 (Soil Water-Ground Water) Parameter.

X26 = soil-water percolation

Three additional parameters were defined:

> X30 = irrigation diversion deviation
> X31 = irrigation runoff
> X32 = 1.0, a system constant

Unity-Coefficient Equations

The five subsystems gave rise to five balance equations:

1) $X1 - X2 - X3 + X4 + X6 + X11 + X18 - X19 - X27 + X28 - X31 = 0$

2) $X13 - X14 + X15 - X16 - X17 + X18 + C(9,22)X22 + C(9,31)X31 = 0$

3) $X5 + X12 - X13 + X17 - X19 - X20 - X21 - X22 + X27 + X28 + C(15,31)X31 = 0$

4) $X7 - X8 + X9 - X10 - X11 + X12 - X26 = 0$

5) $X21 + C(16,22)X22 + X23 - X24 - X25 - X26 = 0$

$C(9,22) = 1.0$ when $T \leq 32^{\circ}$, otherwise $C(9,22) = 0$;

$C(9,31) = 1.0$ when $T \leq 32^{\circ}$, otherwise $C(9,31) = 0$;

$C(15,31) = -1.0$ when $T > 32^{\circ}$, otherwise $C(15,31) = 0$;

$C(16,22) = 1.0$ when $T > 32^{\circ}$, otherwise $C(16,22) = 0$

For parameters other than measured data and those that can be obtained from the balance equations, empirical relationships were obtained either from the annual model by scaling them accordingly or by choosing a relationship as given in the third volume of <u>Development of a State Water Planning Model</u> (Montana University 1972). The empirical relationships follow.[1]

Stream-Reservoir Evaporation Loss

1) $X6 = C(1,2)X2 + C(1,19)X19 + C(1,28)X28 + C(1,31)X31 + C(1,32)X32$
C(i,j) equals the coefficient for the jth variable in the ith row. For X6, all coefficients are temperature dependent, and the exact relationship varied from one subbasin to the next. The general expression for these coefficients for this equation is:

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[1] This system of equations uses unity coefficients, C(i,j) coefficients, and $\bar{C}$ (i.j) coefficients. Unity coefficients normally belong to a balance equation and remain the same for all subbasins. C(i,j) coefficients are temperature-dependent coefficients that vary from one subbasin to another. $\bar{C}$ (i,j) coefficients are independent of the temperature and usually are obtained from the annual model either by scaling down the coefficients or carrying them as they are. C(i,j) and $\bar{C}$ (i,j) coefficients may be found in appendix B.

$C(i,j) = aT + bT^2$

where: T = actual temperature

a and b = constants selected so that the curve of the function duplicates the curve made when evaporation loss is plotted against temperature

The losses due to evaporation are proportionately larger at higher temperatures than at lower temperatures. This nonlinearity with temperature is built into these coefficients. Note that, except for X32, all flows are streamflows, and the losses are called stream losses. The coefficient C(1,32) accounts for the losses from the reservoirs. The coefficient C(1,32) is calculated in subroutine SURFAC as follows by multiplying the pan evaporation coefficient by reservoir surface area.

Stream-Reservoir Percolation

2) $X11 = \overline{C}(2,3)X3 + \overline{C}(2,4)X4 + \overline{C}(2,19)X19 + \overline{C}(2,22)X22 + \overline{C}(2,28)X28 + \overline{C}(2,31$

These coefficients do not depend on temperatures, and are usually obtained from the annual model. $\overline{C}(2,3)$ equals $\overline{C}(2,4)$ which equals 1/12th of the corresponding annual coefficient. $\overline{C}(2,2)$ has the same value as the corresponding annual coefficient (C value).

Ground-Water Discharge

3) $X12 = \overline{C}(3,9)X9 + \overline{C}(3,10)X10 + (C3,32)X32$

The values for $\overline{C}(3,9)$, $\overline{C}(3,10)$ and $\overline{C}(3,32)$ are obtained by dividing the corresponding annual coefficients (C values) by 12.

Sublimation

4) $X14 = C(4,15)X15 + C(4,16)X16$

Sublimation losses were considered to be 2 to 5 percent of the snow cover. A sublimation loss is actually a function of dew point, wind, and temperature, but except for temperature no other data are readily available. Since the losses are not high, an average value was used for all winter months irrespective of the temperature. The average value changed from one subbasin to next.

Snowmelt

5) $X17 = C(5,13)X13 + C(10,15)X15$

$$C(5,13) = \frac{A}{2}$$

C(10,15) = A

where: A = [illegible]

T = actual temperature

D = number of degrees above 32 at which all snow melts.

KS and KT are the factors which affect the rate of snowmelt. The first component in the above expression accounts for the temperature effect on snowmelt, whereas the second one considers the impact of rainfall on snowmelt rate. In the event that A is greater than 1.0, A is set equal to 1, thus ensuring that snowmelt will not exceed the snowpack.

Ground-water Runoff plus Irrigation Runoff

6) X19 = C(6,12)X12 + C(6,27)X27 + C(6,28)X28.

Runoff Evaporation Loss

7) X20 = C(7,5)X5 + C(7,12)X12 + C(7,17)X17 + C(7,28)X28

8) X21 = C(8,12)X12 + C(8,27)X27 + C(8,28)X28

Terminal Surface Water Storage

9) X24 = X21 + C(9,22)X22 + X23 - X25 - X26 when FC_{Min} < X24 < FC

X24 = FC_{Min} when X24 < FC_{Min}, and

X24 = FC when X24 > FC

where: FC_{Min} = minimum soil moisture capacity

Evaporation Loss

10) X25 = X21 + C(10,22)X22 + X23 - X24 - X26

X25 = PET, when X24 > FC_{Min}

where: PET = potential evapotranspiration

Percolation

11) X26 = C(11,21)X21 + C(11,22)X22 + C(11,23)X23 + C(11,32)X32

C(11,32) = BE(X24-FC) when X24 > FC, otherwise C(11,32) = 0

where: RE is a fraction between 0 and 1.

The term (X24 - FC) is the excess water that soil cannot absorb and hence it must either be runoff or should percolate into ground water or both. RE(X24 - FC) is the amount of excess water that goes into ground water.

Precipitation Runoff or Balance

12) $X31 = X1 - X2 - X3 + X4 + X6 + X11 + X18 - X19 + X28$

These twelve equations coupled with balance equations 2 through 5 (the first balance equation and the precipitation runoff equation are equivalent) constituted the monthly model. There were five fewer equations in this model than the model developed at the Water Resources Research Center under Boyd and Williams (1972), mainly due to the different treatment of equations for X7, X8, and X13 and the elimination of equations for X18 and X30. Since X7, X8, and X13 depend on known quantities X1, X2, and X5, respectively, there was no need to consider them as a part of the system of equations for the solution procedure. Equations for X18 and X30 were considered to be unnecessary for the study. Exclusion of these equations reduces the matrix size from 21 x 21 to 16 x 16 and thereby reduces cost in computer time by 30 to 40 percent. Calculations for X7 and X8 are carried out in the mainline program, whereas X13 (the snowfall system) is obtained from the subroutine COMPUT.

CALIBRATION OF THE MONTHLY MODEL AND CONTROLLABLE VARIABLES

Though the monthly model was derived from the annual model, it still needed calibration. The calibration procedure was similar to the one used in the annual model, except that the number of controllable variables was larger than for the annual model. Some of the important controllable variables follow.

Rainfall Moving Average

Outflow from a basin, besides being a function of many variables, was dependent on the precipitation in that basin. Furthermore, all the outflow in a given month was not necessarily due to all the precipitation in that month. It is more than likely that the precipitation in a month influences the outflow for up to a month or two later. For the calibration of the Yellowstone River Basin, the precipitation effect was carried over to the next month. For months when all precipitation was determined to be snowfall, the precipitation averaging was ignored.

$$E = a(g) + (1-a)t$$

where: E = effective rainfall

a = fraction of precipitation in a month resulting in outflow in that month

p = current month's precipitation

t = previous month's precipitation

Snowfall and Snowmelt

The snow subsystem serves as a mechanism in the model to delay the runoff due to snowfall from the winter months when the snow falls to the summer months when it all melts.

$$X13 = \left(1 - \frac{T-b}{32}\right)(X5)$$

where: $X13$ = snowfall

T = temperature in degrees Fahrenheit

b = temperature in degrees Fahrenheit below which all precipitation is snowfall

$X5$ = precipitation

The value of b was chosen with the topography of the area and the climate conditions in mind. For example, in the Bighorn Subbasin, the value of b was $20^{\circ}F$.

The snowmelt rate was another important factor in the calibration phase of the monthly model. Spring runoffs from the basin were mainly due to the snowmelt, and runoff and snowmelt were matched to reflect the cause and effect relationship. From the system of equations, one can see that the snowmelt was a prime component of the soil moisture system, which in turn was a major contributor to the ground water recharge. Thus, a snowmelt rate eventually affected the ground water, potential evapotranspiration, and runoff.

Soil Water Percolation Rate

$$X26 = SF \frac{(X5 + X23)}{(d + X5 + X23)}$$

where: $X26$ = soil water percolation

SF = scaling factor

$X5$ = precipitation

$X23$ = initial soil water storage

d = dampening factor

The term $\frac{(X5 + X23)}{(d + X5 + X23)}$ takes into account the effect of precipitation and the soil moisture condition on the pecolation rate. The dampening factor d is in most cases equal to 1.0, and by changing the value of SF the ground water recharge could be changed.

Initial values for the above controllable variables were selected using experience and knowledge of the basin. The initial run was then made. The output from this run became the basis for making changes in some of the controllable variables, and the model was rerun. This iterative process was continued until:

1) The initial ground water storage equaled the terminal ground water storage for the study period;

2) The average ground water storage equaled the average ground water storage from the annual model; and

3) The total system loss in the monthly model equaled the total system loss in the annual model.

The first two conditions were easier to satisfy than the third condition. For the third condition, a variation up to 5 percent was considered to be acceptable, whereas the first two conditions were met well within the second decimal place of accuracy. The monthly model was said to be calibrated if all of the three conditions were satisfied simultaneously.

The system of equations for the calibration of a subbasin are gathered below:

1) $X6 = C(1,2)X2 + C(1,19)X19 + C(1,28)X28 + C(1,31)X31 + C(1,32)X32$

2) $X10 = X7 - X8 + X9 - X11 + X12 - X26$

3) $X11 = \overline{C}(3,2)X2 = \overline{C}(3,3)X3 + \overline{C}(3,4)X4 + \overline{C}(3,19)X19 + \overline{C}(3,28)X28 + C(3,31)X31$

4) $X12 = \overline{C}(4,9)X9 + \overline{C}(4,10)X10 + \overline{C}(4,32)X32$

5) $X14 = C(5,15)X15 + C(5,16)X16$

6) $X16 = X13 - X14 + X15 - X17 + X18 + C(6,22)X22 + C(6,31)X31$

7) $X17 = C(7,13)X13 + C(7,15)X15$

8) $X19 = C(8,12)X12 + C(8,27)X27 + C(8,28)X28$

9) $X20 = C(9,5)X5 + C(9,12)X12 + C(9,17)X17 + C(9,28)X28$

10) $X21 = C(10,12)X12 + C(10,27)X27 + C(10,28)X28$

11) $X22 = X5 + X12 - X13 + X17 - X19 - X20 - X21 + X27 + X28 + C(11,31)X31$

12) $X24 = X21 = C(12,22)X22 + X23 - X25 - X26$, when $FC_{Min} \leq X24 \leq FC$

$X24 = FC_{Min}$, when $X24 < FC_{Min}$

$X24 = FC$, when $X24 > FC$

13) $X25 = X21 + C(13,22)X22 + X23 - X24 - X26$, when $X26 > FC_{Min}$

$X25 = FC1$, when $X25 < FC_{Min}$

14) $X26 = C(14,21)X21 + C(14,22)X22 + C(14,23)X23 + C(14,32)X32$

$C(14,32) = PF(X24 - FC)$ when $X24 > FC$, otherwise $C(14,32) = 0$

15) $X29 = X28$ (Dummy Equation)

16) $X31 = X1 - X2 - X3 + X4 + X6 - X11 + X18 - X19 + X27 + X28$

CALIBRATION PROGRAM AND NEW SUBROUTINES

Although the calibration program used in the Yellowstone Impact Study was essentially the same as the one prepared by the Montana Water Resources Research Center (Boyd and Williams 1972), the program was modified to make the logic less dependent on the basin parameters. In the original version of the model,basin parameters were fed into the main program and the program was run. If the model was used for some other basin with different parameters, the corresponding changes would have had to be incorporated and the whole program would have had to be run again. Three subroutines--INITIA, EXPORT, and SURFAC-- were added and one subroutine--COMPUT--was modified in order to make the logic less dependent on the basin parameters. The result was an essentially data and basin independent calibration program that could be easily used on all nine subbasins.

Figure 6 shows the hierarchy of the subroutines and their relationship to each other. These subroutines were called from left to right.

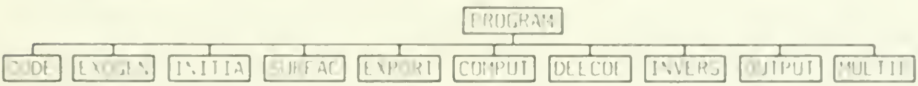


Figure 6. Calibration program subroutines

A brief description of the new subroutines is given below.

INITIA

The initial values for different subbasins could be read either through changes in the subroutines or from the data card. In the original program, the following initial values were specified in the main logic, and the whole program was compiled and run. If the initial values changed, the original program had to be recompiled.

The initial values specified were:

1) Initial precipitation for averaging precipitation (SAVE):

2) Field capacity (FC) and minimum field capacity (FC_{Min});

3) Coefficients for moving average rainfall (Q);

4) Beginning year and ending year (M,N); and

5) Number of months (NP).

Since these values could be read outside the main program, the rest of the revised program was subbasin independent. With this idea in mind, the subroutine INITIA was created. The values that were read into INITIA are:

1) SAVE--initial precipitation for averaging;

2) FC, FC_{Min}--field capacity, minimum field capacity;

3) Q--precipitation averaging factor;

4) M,N--beginning and ending year;

5) R1,P1--coefficients for calculating X7 (ground-water outflow);

6) R2,P2--coefficients for calculating X8 (ground-water inflow);

7) RE--groundwater recharge factor (ground-water recharge due to saturation of field capacity);

8) NP--number of months for study period; and

9) MP--number of months for calibration.

In most cases, the number of months for study period should be the same as for calibration, however, if calibration is for a shorter period MP would be different from NP.

Note that the subroutine INITIA has coefficients for calculating X7 (ground-water outflow) and X8 (ground-water inflow). The following relationships were used to calculate X7 and X8:

$$X7 = (P1)(X1) + R1$$

$$X8 = (P2)(X2) + R2$$

where: X1 = outflow from the basin

X2 = inflow to the basin

Since X1 and X2 were primary values (i.e., they were read in as an input to the system) X7 and X8 could also be read in as primary values because of the above relationships.

In the original program, X7 and X8 were a part of the system of equations. This increased the matrix size. As mentioned above, X7 and X8 did not need to belong to this system of equations, since their values were known as soon as

X1 and X2 were known. This feature was exploited in reducing the matrix size. With the addition of [illegible] to the program, [illegible] and [illegible] are calculated right after X1 and X2 are read.

EXPORT

This subroutine was added to handle exports from the subbasin. The export variable S(27) may, at times, have depended on the month NM. In case that export was zero, S(27) = 0 for all NM. NM = month considered.

SURFAR

In the original calibration program, evaporation loss from the reservoir was calculated as a certain percentage of the storage. More accurate evaporation losses may be calculated by multiplying the pan evaporation coefficient by surface area.

When the daily pan evaporation coefficient was available, there was no need for any correction, such as for wind or humidity. Multiplying the pan evaporation coefficient by the surface area gives a fairly accurate estimate of evaporation losses. Since the unit of time for the study was one month, the average pan evaporation coefficient value for the month could be used without any correction factor.

This subroutine could take 36 storage levels in some uniform steps. The actual surface area was interpolated linearly between two adjacent levels.

COMPUT

In the original program, snowfall had been treated as a part of the system of equations. Since snowfall is a function of precipitation and temperature, both of which are known, snowfall could be calculated outside the system of equations. The COMPUT subroutine was modified to calculate snowfall. Other than this change, this subroutine was essentially the same as the original subroutine.

SIMQUAL-- THE SIMULATION PROGRAM

Although SIMQUAL, as the modified simulation program was named, retained the basic character of the original SWP model, SIMQUAL contained some new features which included water quality calculations, changes in the output format, and different criteria for the operation of reservoirs. The SIMQUAL program had many new subroutines compared to the original SWP program (Montana University 1972). Figure 7 shows the hierarchy of SIMQUAL's subroutines.

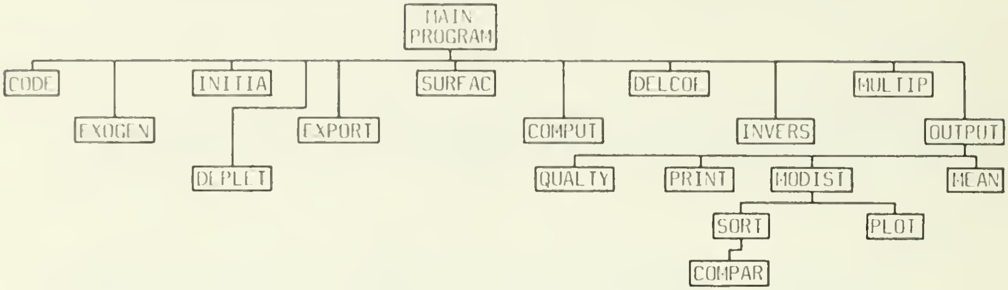


Figure 7. Simulation program subroutines

Subroutines DEPLET, COMPUT, SURFAC, EXPORT, INITIA, and QUALTY were subbasin dependent; all others were subbasin independent.

Subroutines common to the simulation and calibration programs (those which occur both in figure 6 and in figure 7) remained essentially the same except COMPUT. Changes in the COMPUT subroutines were due to rearrangement of the system of equations. The new subroutines are described briefly.

DEPLET

This subroutine, added to the main program, handled any reallocation of water as between two states or regions. As an example, for the Yellowstone Impact Study, inflows from the Tongue River, the Powder River, or the Bighorn River had to be reduced to allow for Wyoming's share of water from these rivers. The amount to be allocated was based on the compact between the two states. As the name implies, this subroutine allowed for this depletion. During the simulation phase, any changed inflow to the subbasin may be read in the subroutine DEPLET. Arguments of the subroutines are month IT and inflow S(2).

SURFAC

Subroutine SURFAC calculated the evaporation loss from a reservoir based on the surface area of the reservoir and the pan evaporation coefficient for that month. It is assumed that the average value of a pan evaporation coefficient for each month will take into account factors such as temperature, humidity, and wind on an average basis.

INITIA

This subroutine defined the initial values of some of the By creating this subroutine, the main program became independent of the subbasin and scenarios.

MODIST

MODIST was a short form of monthly distribution, ranking the data on a monthly basis and finding ninetieth percentile and median values (i.e. flows that are exceeded in 90 percent of those months and 50 percent of those months, for a particular month). It also calculated the mean value on a monthly basis. For ranking the data, subroutines SORT and COMPAR were called. Subroutine PLOT was called to plot the ninetieth percentile and fiftieth percentile values. Arguments of the subroutine were NMO, AA, and YY. AA corresponds to monthly data, NMO is number of months, YY, if zero implies water quality year, otherwise water year.

QUALTY

This subroutine was called by the OUTPUT subroutine to calculate total dissolved solids (TDS) based on outflow.

Arguments of the subroutine QUALTY were Q, RF, DIV, EN, OF, II, TDS, TDSF, TDSQ, TDSL, TDSL1, TDSF1, TDSL2, and TDSF2 where:

Q = outflow or release;

RF = return flow;

DIV = diversion requirement (irrigation plus energy and instream flows);

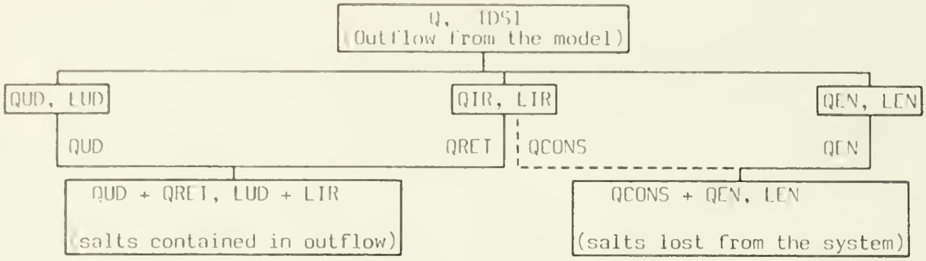
EN = energy flow;

OF = outflow RF plus instream plus spill; and

II = counter on month.

These arguments, required for TDS calculations, were transferred back to the OUTPUT routine for further calculations and output.

TDS calculations are shown schematically in figure 8.



where: Q = net outflow = QUD + QIR + QEN

QUD = undiverted water in million acre-feet

QIR = diverted irrigation water in million acre-feet = QRET + QCONS

QRET = return flow in million acre-feet

QCONS = consumptive use of diverted irrigation water in million acre-feet

QEN = energy plus consumptive industrial water

LUD, LIR, LEN = total dissolved solids in tons in QUD, QIR, and QEN, respectively.

Figure 8. Schematic representation of TDS calculations.

Figure 8 shows that the total salt lost from the system was due to industrial or energy water. Salts in the irrigation diversion were assumed to come back to the mainstem through return flow. Thus the outflow was QUD + QRET with total load of LUD + LIR.

TDS was calculated using a monthly regression equation:

TDS = f(Q,c)

where: Q = flow in million acre-feet;

c = a constant; and

f = a function giving the relationship between TDS and (Q,c)

$$LUD = TDSI(QUD)$$

$$LIR = TDSI(QIR)$$

$$LEN = TDSI(QEN)$$

$$\text{Outflow } TDSI = \frac{LUD + LIR}{QUD + QRET}$$

In addition to finding the outgoing quality, the following quantities were also calculated in this subroutine:

1) Total load diverted in tons for irrigation, TDSI;

2) TDS in parts per million, TDS(II);

3) Outgoing load in tons, TDSL(II);

4) Outgoing TDS, TDSF(II);

5) Total load in the stream TDSQ(II);

6) Total outgoing load with half ton/acre salt pick up, TDSL1(II);

7) Total outgoing load with one ton/acre salt pick up, TDSL2(II); and

8) TDSF1(II), TDSF2(II) outgoing water quality with half-ton and one-ton salt pick up per acre, respectively.

Water quality calculations were based on yearly intervals extending from April through March, whereas other calculations were based on the water year which extends from October through September. Consequently, the first six months and the last six months of the thirty-year study period were ignored in water quality calculations.

The total load in tons that was diverted for irrigation is from April through October. This diverted load returned to the stream during the same year--April through March--with the distribution shown in table 46.

Table 46. Percentage by month of TDS returning to streamflow.

Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
49%	11%	14%	18%	18%	10%	8%	5%	4%	3%	2%	3%

The subroutine QUALTY was called after every simulated twelve months. This was mainly due to different amounts of salt load in the stream from one year to the next.

PRINT

This subroutine was primarily meant for printing headings on the monthly values of outflow, inflow, and water quality in TDS. Arguments of the subroutine were AA, NMO, and YY. AA corresponded to monthly data, NMO to the number of months, and YY, if zero, implied water quality year (April through March), otherwise water year.

MEAN

This subroutine mainly calculated the simple average or time weighted average and volume weighted average of TDS. These averages were calculated by the month and also by the year. Arguments of the subroutine were NMO, AA, BB, and YY. AA contained TDS data and BB, the flow data. NMO and YY have the same meaning as defined above.

SORT and COMPAR

These subroutines were called by the MODIST subroutine for ranking the data in ascending order.

PLOT

Subroutine PLOT plotted the fiftieth and ninetieth percentile values (i.e. those values exceed 50 and 90 percent of the time) of outflow, inflow, and water quality. Arguments of the subroutine were NMO, AA, BB, SF, and YY. AA corresponded to fiftieth percentile data and BB represented ninetieth percentile data. SF was the scale factor and equaled 80 percent of the largest value of fiftieth percentile data; YY, if zero, implied water quality year, (April through March), otherwise water year.

Simulations

TYPES OF SIMULATION

When all subbasins had been calibrated, they were ready for simulation runs. An ideal model--for simulation is the one that allows a wide range of operating criteria to be used in each simulation. Unfortunately, most models can carry out simulations only over a given set of rules and a limited number of operating criteria. The SWP model is no exception.

In this study, the SWP was used to study three types of simulations.

Type 1

In type 1 simulations, the operating rules were to release water from the reservoir to meet the minimum flow requirement, to keep storage as high as possible, but to give releases to maintain minimum flows a higher priority than storage. Under such conditions, the annual yield was the maximum amount of water that could be withdrawn from the reservoir for each year of the study period while maintaining a minimum storage level.

Type 2

In type 2 simulations there was no storage in the basin and consequently what could not be used was lost from the system. The maximum amount of water that could be used was dictated by the minimum flows in the study period.

Type 3

Type 3 simulations differed from type 1 in the operating policy. The operating policies were to release water from the reservoir to give the irrigation demand highest priority and always satisfy that demand (d), and to store water in the dam if the inflow to the dam exceeded the demand plus the reservations for minimum flows. If the inflow was less than the demand d, then the flow was augmented by the release from the dam to meet the demand d. If the inflow was less than $\zeta + d$, where ζ is the minimum required flow, but more than d, then nothing could be stored and inflow was passed through the dam. If inflow exceeded $\zeta + d$, the excess inflow over $\zeta + d$ could be stored, if storage space were available.

The simulation program as written by Boyd and Williams (1972) was useful for type 1 simulations. The main logic of the program had to be modified to include type 3 simulations. Besides changing the logic, the simulation program was modified to include water quality calculations based on total dissolved solids (TDS).

SCENARIOS

Each subbasin had up to three scenarios for simulating high, intermediate, and low water use. In each scenario the demands for irrigation, energy, and municipal use were lumped together. The model in this form did not discriminate among the demands explicitly based on their use; however, it discriminated among them indirectly whenever necessary. For example, if the total demand for irrigation, energy, and municipal water could not be satisfied for the period of study, then the program assumed that the irrigation and municipal demands had a higher priority than the energy demand. Satisfying the irrigation and municipal demands implied that although all of the irrigation and municipal demands could be satisfied, there would not be enough water to meet all of the energy demand. The same model could be run satisfying part of the energy demand. Finding the demand that could be satisfied was essentially the same as finding the yield of the subbasin. Since the quality of water leaving the subbasin was a function of irrigation diversion return flows, it was important to identify the satisfied demands.

For subbasins that had no reservoir, the portion of the logic for storing water was eliminated and other portions of the program were changed.

In type 3 simulations, the data were arranged in a different way. For example,[1] suppose that the total demand for irrigation plus energy, municipal, and instream requirements is d and the minimum flow demand is δ. As per the operating rule, water can be stored if the inflow exceeds $\delta + d$. The dam can release water to meet d, but can release no water to augment the flows for the minimum flow requirement. The demand d is read in as RA(I) in the program and $d + \delta$ is read in as FG(I). The decision to store or to release water is determined by the inflow. If the inflow exceeds FG(I), water can be stored. The amount to be stored will depend on the storage level. In case the inflow is between RA(I) and FG(I) there would be no need to augment the flows since demand RA(I) would be satisfied. Water would not be stored because the inflow is less than FG(I). For inflows less than RA(I), flows would be augmented to meet demand RA(I). The main consequence of the above mentioned operating rule was the reduction in the yield of the subbasin, because the reservoirs were not allowed to store as much as they could.

In simulation, the system of equations used was exactly the same as used in calibration with the exception of the role played by the following equation:

$$X31 = X1 - X2 - X3 + X4 + X6 + X11 + X18 - X19 + X27 + X28$$

The above equation was used for solving for X31 in the calibration phase, but in the simulation this was used for solving for X1 or X4.

$$X1 = X2 + X3 - X4 - X6 - X11 - X18 + X19 - X27 - X28 + X31$$

or

$$X4 = X1 + X2 + X3 - X6 - X11 - X18 + X19 - X27 - X28 + X31$$

---

[1] An implicit assumption in this logic is that the demand d has higher priority than the minimum flow demand, but this can be changed if necessary.

Thus, by interchanging the role of X1 or X4 with X31, the same equation could be used in simulation.

When the above equation was used for solving for X1, the set of equations was said to be in mode 1. When solving for X4, it was said to be in mode 4. The equations for the simulation follow:

1) $X1 = X2 + X3 - X4 - X6 - X11 - X18 + X19 - X27 - X28 + X31$

2) $X6 = C(2,2)X2 + C(2,19)X19 + C(2,28)X28 + C(2,31)X31 + C(2,32)X32$

3) $X10 = X7 - X8 + X9 - X11 + X12 - X26$

4) $X11 = \overline{C}(4,2)X2 + \overline{C}(4,3)X3 + \overline{C}(4,4)X4 + \overline{C}(4,19)X19 + \overline{C}(4,28)X28 +$
$C(4,31)X31$

5) $X12 = C(5,9)X9 + C(5,10)X10 + \overline{C}(5,32)X32$

6) $X14 = C(6,15)X15 + C(6,16)X16$

7) $X16 = X13 - X14 + X15 - X17 + X18 + C(7,22)X22 + C(7,31)X31$

8) $X17 = C(8,13)X13 + C(8,15)X15$

9) $X19 = C(9,12)X12 + C(9,27)X27 + C(9,28)X28$

10) $X20 = C(10,5)X5 + C(10,12)X12 + C(10,17)X17 + C(10,28)X28$

11) $X21 = C(11,12)X12 + C(11,27)X27 + C(11,28)X28$

12) $X22 = X5 + X12 - X13 + X17 - X19 - X20 - X21 - X27 + X28 + C(12,31)X31$

13) $X24 = X21 + C(13,22)X22 + X23 - X25 - X26$ when $FC_{Min} < X24 < FC$

$X24 = FC_{Min}$ when $X24 < FC_{Min}$

$X24 = FC$ when $X24 > FC$

14) $X25 = X21 + C(14,22)X22 + X23 - X24 - X26$ when $X24 < FC_{Min}$ otherwise

$X25 = PET$

15) $X26 = C(15,21)X21 + C(15,22)X22 + C(15,23)X23 + C(15,32)X32$

where: $C(15,32) = RE(X24 - FC)$ when $X24 = FC$, otherwise

$C(15,32) = 0$

16) $X29 = X28$ (Dummy equation).

Reordering of equations and coefficients was necessary becamse of the inverse subroutine used in the program. The logic was changed from mode 1 to mode 4 and vice versa, depending upon the storage condition. If the storage was full, the system was solved for outflow X1, and hence mode 1, otherwise, in mode 4.

AREA SIMULATIONS

THE UPPER YELLOWSTONE, CLARKS FORK YELLOWSTONE, AND KINSEY AREA SUBBASINS

These three subbasins were not simulated. Rather the projected water requirements for these subbasins for each of the three levels of development were merely subtracted from their historical outflow, so that the simulations for downstream subbasins would reflect all upstream water use in addition to their own.

THE BILLINGS AREA SUBBASIN

Inflow to the Billings Area Subbasin for a particular level of development was the sum of the outflows from the Upper Yellowstone and Clarks Fork Yellowstone subbasins for the same level of development. By using a similar procedure for each subbasin, the cumulative effect of development could be simulated for the lower subbasins in the Yellowstone basin.

The water requirements for the low, intermediate, and high levels of development in the Billings Area Subbasin are shown in table 47. These requirements reflect only the water that would be needed to meet irrigation and municipal demands. None of the levels of development called for water to meet energy demands or minimum-flow requirements. For all three levels of development, flows would be neither augmented nor stored because the subbasin has no dam to regulate flows.

The results of the simulations of the three levels of development are shown in tables 48 and 49. The simulation indicated that the Billings Area Subbasin would have enough water to meet the demands of a high level of development, although the demands would reduce the flows in June, July, August, and September below their historical levels. The demands of the low and intermediate levels of development would not significantly reduce historical flows. Generally, none of the simulations indicated appreciable degradation of water quality although it is likely that the few low-flow months under the high level of development would result in a drastic degradation in water quality.

THE BIGHORN SUBBASIN

Because of the presence of the Yellowtail Dam, the Bighorn Subbasin would meet its demands under high and intermediate levels of development. The low level of development was not considered for this subbasin because the water

requirements would be insignificant compared to the historical flow of the river. Table 50 shows the flow requirements for the intermediate and high levels of development. These flow requirements include energy, irrigation, and municipal demands but no minimum-flow requirements. In both levels of development, it was assumed that the Yellowtail Dam would be available to augment or store streamflows throughout the simulation period. A depletion allowance consistent with the Yellowstone River Compact was made in the Bighorn Subbasin's inflows.

Table 47. Billings area Subbasin water requirements (in acre-feet).

Month	Projected Level of Development		
	Low	Intermediate	High
Oct	485	685	905
Nov	290	295	325
Dec	290	295	325
Jan	290	295	325
Feb	290	295	325
Mar	290	295	325
Apr	485	685	905
May	2,815	5,240	7,895
June	3,590	6,895	10,235
July	6,500	12,715	18,955
Aug	5,140	10,000	14,880
Sept	2,425	4,565	6,730
TOTAL	22,890	42,260	62,130

The results of the simulations of the high and intermediate levels of development are shown in table 51. The demands of the high level of development would easily be satisfied without affecting natural flows significantly, although the ninetieth-percentile flows (those flows exceeded 90 percent of the time in a given month) would be low for July and August. This, however, was due to the operational policy used for the dam in the simulation. In any event, a release from the dam exceeded the requirement only if it was a spill from the dam. Like the high level of development simulation, the intermediate level of development simulation indicated little effect on the natural outflow.

In either case, the water quality of the outflow would remain almost unchanged from the natural outflow's water quality because the total demand for both simulations would be small compared to the natural outflow. Total dissolved solids would vary from 477 to 634 mg/l for the intermediate level and from 477 to 650 mg/l for the high, a small range due to the Yellowtail Dam which reduces fluctuations in water quality.

Table 48. Outflow of the Billings area subbasin (in acre-feet).

Month	Level of Development					
	Low		Intermediate		High	
	Fiftieth percentile	Ninetieth percentile	Fiftieth percentile	Ninetieth percentile	Fiftieth percentile	Ninetieth percentile
Oct	245,036	163,456	244,956	163,380	244,866	163,295
Nov	219,666	188,062	219,982	188,379	220,263	188,660
Dec	178,411	133,290	178,661	133,545	178,882	133,769
Jan	153,036	100,470	153,219	100,663	153,367	100,820
Feb	159,451	120,568	159,567	120,690	159,657	120,787
Mar	210,452	143,850	210,636	144,040	210,786	144,195
Apr	241,904	167,308	241,574	166,985	241,219	166,637
May	697,674	360,719	691,032	334,079	684,165	327,214
June	1,545,894	1,065,127	1,537,069	1,056,308	1,528,209	1,047,449
July	804,278	379,376	787,143	362,245	769,993	345,099
Aug	230,954	119,876	217,809	106,737	204,654	93,589
Sept	184,038	108,507	178.382	102,850	172,690	97,157

NOTE: A fiftieth-percentile flow is the flow that is exceeded 50 percent of the time in a particular month, and the ninetieth-percentile flow is that flow that is exceeded 90 percent of the time in a particular month.

Table 49. Average outflow (in acre-feet) and TDS (in mg/l) of the Billings area subbasin

Month	Level of Development						Natural Flow
	Low		Intermediate		High		
	Flow	TDS	Flow	TDS	Flow	TDS	
Oct	248,041	268	247,966	269	247,881	270	262,944
Nov	227,485	278	227,776	279	228,059	279	227,424
Dec	173,022	305	173,270	306	173,488	306	173,048
Jan	153,559	312	153,747	312	153,900	313	153,655
Feb	167.798	289	167,916	289	168,009	290	167,954
Mar	222,461	267	222,650	268	222,803	268	222,558
Apr	249,442	253	249,117	253	248,768	254	253,506
May	688,842	156	682,185	156	675,321	157	746,377
June	1,565,048	117	1,556,220	117	1,547,358	118	1,636,944
July	830,338	131	813,202	132	796,052	134	932,201
Aug	252,659	228	239,513	231	226,358	235	344,169
Sept	199,550	283	193,892	286	188,199	289	263,177
TOTAL	4,978,245		4,927,454		4,876,196		5,383,957

Table 50. Bighorn subbasin water requirements (in acre-feet)

Month	Level of Development	
	Intermediate	High
Oct	750	2,775
Nov	490	2,385
Dec	490	2,385
Jan	490	2,385
Feb	490	2,385
Mar	490	2,385
Apr	750	2,775
May	3,880	7,470
June	4,920	9,035
July	8,830	14,900
Aug	7,010	12,170
Sept	3,360	6,685
TOTAL	31,950	67,735

Table 51. Outflow (in acre-feet) and TDS (in mg/l) of the Bighorn Subbasin

Month	Level of Development							
	Intermediate				High			
	Fiftieth Percentile	Ninetieth Percentile	Average	TDS	Fiftieth Percentile	Ninetieth Percentile	Average	TDS
Oct	194,045	140,169	197,372	625	188,241	134,252	191,535	627
Nov	184,077	142,153	184,734	631	180,204	138,223	180,780	632
Dec	164,977	109,022	160,842	612	160,974	104,977	156,861	613
Jan	143,349	100,767	153,433	552	139,343	96,807	149,412	554
Feb	144,398	107,600	169,476	477	140,336	103,678	165,413	477
Mar	211,631	157,238	232,825	503	207,573	153,146	228,792	504
Apr	204,188	119,215	201,080	624	198,322	113,168	195,063	626
May	259,527	135,198	282,443	592	236,007	109,680	256,963	595
June	566,793	137,846	546,688	594	534,673	105,791	514,631	596
July	261,441	30,130	312,457	579	204,851	2,340	260,706	584
Aug	81,338	36,351	111,056	625	35,368	2,340	67,477	650
Sept	155,622	91,851	157,206	634	131,494	57,261	128,967	640
TOTAL			2,709,612				2,496,600	

NOTE: See note to table 48.

THE MID-YELLOWSTONE SUBBASIN

The water requirements for the low, intermediate, and high levels of development in the Mid-Yellowstone Subbasin are given in table 52. These requirements include demands for energy, irrigation, and municipal use but no minimum flow requirement. The Mid-Yellowstone Subbasin was assumed to have no ability to augment or store flows.

Table 52. Mid-Yellowstone subbasin water requirements (in acre-feet)

Month	Level of Development		
	Low	Intermediate	High
Oct	3,320	6,950	12,700
Nov	3,070	6,445	11,940
Dec	3,070	6,445	11,940
Jan	3,070	6,445	11,940
Feb	3,070	6,445	11,940
Mar	3,070	6,445	11,940
Apr	3,320	6,950	12,700
May	6,350	13,005	21,780
June	7,360	15,025	24,815
July	11,165	22,595	36,160
Aug	9,380	19,055	30,860
Sept	5,845	11,995	20,265
TOTAL	62,090	127,800	218,980

The fiftieth- and ninetieth-percentile outflow values for all simulated levels of development in the Mid-Yellowstone Subbasin are given in table 53. The ninetieth-percentile flows would be high for all months but August. During the simulated month of August 1961, there was some shortage for both the intermediate and high levels of development; this was the only shortage indicated.

The average values of TDS, displayed along with average flows in table 54, indicate that water quality would become slightly poorer during the simulated low flows of 1961, when the large proportion of irrigation return flow in the outflow substantially decreased water quality.

THE TONGUE SUBBASIN

Table 55 gives the water requirements for the Tongue River under the low, intermediate, and high levels of development. The "Projected Demand" columns show demands for irrigation, municipal use, and energy. At the high level of development, not all of the irrigation, municipal, and energy requirements could be satisfied. Since the irrigation and municipal demands have higher priority, only 4,435 acre-feet of the projected energy demand of 9,835

acre-feet per month could be met. For the high level of development, the "Projected Demand" column also shows minimum-flow requirement judged by the Montana Fish and Game Department to be a "bare-bones" requirement: 900 acre-feet per month for June through February, 2700 acre-feet per month for March, April, and May. For the remaining two levels of development, the minimum-flow requirement is shown only in the second column. For the intermediate development level that minimum-flow requirement is 60 percent of the instream flow assumed by the Water Work Group of the Northern Great Plains Resources Program (NGPRP 1974); for the low level of development, all of the NGPRP-assumed instream flow was included. A reservoir with a capacity of 320,000 acre-feet was assumed for the high and intermediate levels of development, and a reservoir with a capacity of 112,000 acre-feet was assumed for the low level of development.

Table 53. Outflow of the Mid-Yellowstone subbasin (in acre-feet)

Month	Level of Development					
	Low		Intermediate		High	
	Fiftieth Percentile	Ninetieth Percentile	Fiftieth Percentile	Ninetieth Percentile	Fiftieth Percentile	Ninetieth Percentile
Oct	462,205	323,536	459,151	320,492	448,648	310,188
Nov	409,310	333,575	406,677	330,930	398,081	322,045
Dec	337,255	217,102	334,446	214,307	325,382	205,456
Jan	296,842	194,918	293,910	191,983	284,947	182,934
Feb	302,286	225,893	299,204	222,809	290,037	213,586
Mar	388,389	294,533	485,442	291,594	476,136	282,481
Apr	465,915	326,058	462,291	322,432	451,155	311,278
May	988,032	439,194	975,673	426,837	935,515	386,800
June	2,129,436	1,175,717	2,114,182	1,160,467	2,064,900	1,111,223
July	1,080,117	408,825	1,053,213	381,985	968,080	325,307
Aug	305,904	142,989	284,700	121,804	215,827	64,785
Sept	342,057	210,790	331,134	199,867	291,202	137,652

NOTE: See note to table 48.

The fiftieth- and ninetieth-percentile flows for the three simulations are given in table 56. The 320,000 acre-foot reservoir used in the intermediate- and high-level simulations could satisfy a total annual demand of about 130,000 acre-feet. The fiftieth- and ninetieth-percentile values would be almost equal for those two levels of development, implying that the outflow consisted only of the irrigation return flows plus instream requirements.

Table 54. Average outflow (in acre-feet) and TDS (in mg/l) of the Mid-Yellowstone subbasin

Month	Level of Development						Natural Flow
	Low		Intermediate		High		
	Flow	TDS	Flow	TDS	Flow	TDS	
Oct	460,062	460	457,015	460	446,660	465	478,565
Nov	417,964	486	415,323	486	406,554	490	423,122
Dec	323,390	558	320,589	558	311,654	562	341,435
Jan	300,485	476	297.545	576	288,413	581	318.323
Feb	344,890	529	341,800	529	332,483	532	368,217
Mar	493,392	441	490,452	441	481,304	443	493,009
Apr	456,588	462	452,962	462	441,822	467	466,004
May	941,441	311	929,090	313	889,073	320	1,013,584
June	2,103,569	198	2,088.318	201	2,039,064	203	2,164,446
July	1,166,987	269	1,140,055	271	1,059,693	280	1,326,683
Aug	359,878	504	338,680	508	272,129	530	501,157
Sept	362,990	524	352,061	529	310,895	556	442,866
TOTAL	7,731,636		7,623,890		7,279,744		8,337,411

Table 55. Tongue subbasin water requirements (in acre-feet)

Month	Level of Development				
	Low		Intermediate		High
	Projected Demand	Projected Demand Plus Minimum Flow	Projected Demand	Projected Demand Plus Minimum Flow	Projected Demand
Oct	1,175	7,175	4,370	7,970	6,000
Nov	955	6,955	3,930	7,530	5,400
Dec	955	9,055	3,930	8,790	5,400
Jan	955	9,055	3,930	8,790	5,400
Feb	955	9,055	3,930	8,790	5,400
Mar	955	12,995	3,930	11,130	5,400
Apr	1,175	14,975	4,370	12,650	6,000
May	3,810	29,310	9,335	24,935	13,960
June	4,685	30,185	11,390	26,690	16,595
July	7,985	30,185	17,975	31,300	26,470
Aug	6,445	12,445	14,900	18,500	21,860
Sept	3,370	9,370	8,760	12,360	12,645
TOTAL	33,420	180,760	90,750	179,435	130,530

Table 56. Outflow of the Tongue River subbasin (in acre-feet)

Month	Level of Development					
	Low		Intermediate		High	
	Fiftieth Percentile	Ninetieth Percentile	Fiftieth Percentile	Ninetieth Percentile	Fiftieth Percentile	Ninetieth Percentile
Oct	6,585	1,562	4,770	1,170	2,655	2,655
Nov	6,365	4,943	4,335	2,538	1,997	1,997
Dec	8,390	5,667	5,665	2,862	1,778	1,778
Jan	8,320	7.379	5,300	4,624	1,558	1,558
Feb	8,245	5,834	5,150	2,745	1,339	1,339
Mar	23,812	12,260	7,640	7.640	3,358	3,358
Apr	23,129	11,375	8,860	5,133	3,578	3,578
May	44,807	15,337	17,205	9,237	5,113	5,113
June	103,865	4,479	57,310	2,045	40,320	3,472
July	13,994	1.315	2,630	2,630	4,849	4,849
Aug	1,315	1,315	2.630	2,630	4,849	4,849
Sept	6.730	730	4,182	1,460	3,094	3,094

NOTE: See note to table 48.

Table 57. Average outflow (in acre-feet) and TDS (in mg/l) of the Tongue subbasin

Month	Level of Development						Natural Flow	Incoming TDS
	Low		Intermediate		High			
	Flow	TDS	Flow	TDS	Flow	TDS		
Oct	9,078	516	4,567	752	2,744	779	16,995	607
Nov	9,832	670	4,816	766	2,261	793	18,369	696
Dec	9,964	739	5,514	798	2,080	835	12,893	756
Jan	10,496	675	5,609	753	2,168	768	11,092	719
Feb	16,584	412	8,740	464	3,992	494	16.414	491
Mar	40,952	416	26,354	432	20,830	422	39,248	431
Apr	27.936	542	18,732	560	14,194	555	32,325	550
May	51,155	440	36,080	470	26,765	464	48,955	443
June	101,622	262	76,818	283	65,115	285	95,469	265
July	18.857	381	11,263	517	8,453	562	30,657	348
Aug	2,589	857	2,869	1,137	4,849	768	9,397	423
Sept	6,391	597	3,700	785	3,094	752	12,167	507
TOTAL	305,456		205,062		156,545		343,981	

Table 57 gives the values of average outflows and levels of TDS for each level of development in the Tongue Subbasin. Under the low level of development, water quality calculations showed only slight degradation. Under the intermediate level of development, TDS calculations indicate a slight deterioration in water quality. Because most of the outflow during August would consist of irrigation return flows, that month would have the worst water quality. At the high level of development, TDS levels indicate poor water quality in most months, a result of what would be reduced outflow having a large proportion of irrigation return flows. Instream flows would be crucial in maintaining water quality. By increasing the instream requirement, water quality degradation could be reduced, especially in low-flow months.

Under the low level of development, the irrigation, municipal, and energy demand as well as all of the NGPRP-requested minimum flow could be completely satisfied, even assuming the smaller reservoir. The fiftieth- and ninetieth-percentile values (table 56) indicate that August would be the only critical month at this level of development.

For the intermediate level of development, the total water demand was about 91,000 acre-feet. As explained above, the 320,000-acre-foot reservoir would yield 130,000 acre-feet annually, leaving 40,000 acre-feet per year available for other uses. Up to 60 percent of the minimum flow suggested by the NGPRP could be satisfied with this water. This minimum flow would not be augmented by releases of stored water from the dam. If the natural inflow to the reservoir is less than or equal to the minimum-flow requirement, then no water could be stored. If the natural inflow is more than the minimum-flow requirement, then the excess could be stored or used to meet the "projected demand" of table 55. In either case, stored water could be released to meet projected consumptive demand. The fiftieth- and ninetieth-percentile flow values show that, except in July and August, there would be water in the stream in addition to the return flows.

THE POWDER SUBBASIN

Table 58 gives the water requirements used in simulations of the Powder Subbasin. The high level of development called for 230,000 acre-feet for irrigation water alone; the assumed active storage in the subbasin was only 275,000 acre-feet. After five trial simulations, it became apparent that not all of the water demand of the intermediate and high levels of development could be satisfied. Instead, those two projected levels of development were replaced by the "55 percent" level, which consisted of 55 percent of the high-level irrigation demand, the full high-level municipal demand and no water for energy or for minimum-flow requirements. Nor were minimum-flow requirements considered for the low level of development.

Table 58. Powder subbasin water requirements (in acre-feet)

Month	Level of Development	
	Low	55 Percent
Oct	820	1,335
Nov	70	95
Dec	70	95
Jan	70	95
Feb	70	95
Mar	70	95
Apr	820	1,335
May	9,850	16,225
June	12,855	21,185
July	24,140	39,800
Aug	18,870	31,115
Sept	8,345	13,745
TOTAL	76,050	125,215

The simulation recognized Wyoming's 42-percent share of the Powder River's water by including only 58 percent of the historical inflows' values in the simulation, with the exception that in no month were the historical inflows' values reduced by more than 7,140 acre-feet (42 percent of 17,000 acre-feet) regardless of the size of the historical monthly flow.

The annual yield of the subbasin was calculated assuming a reservoir having a yield of 125,000 acre-feet. This yield was based on the assumption that the reservoir's inflow included flows from the Little Powder River, an impossibility at the Moorhead site, which is the most probable location for the reservoir. The 125,000-acre-foot yield might be achieved if two dams were built, one on the Little Powder and one on the Powder.

The results of the simulations are given in table 59.

If a dam were built, the water quality of the river below the dam would be changed. Seasonal variations in water quality would be averaged, resulting in a net improvement in water quality. The amount of improvement is unknown.

Even at the low level of development the irrigation demand would be 76,000 acre-feet, a third of which would come back to the river as return flow. TDS levels would range from 1,000 to 3,400 mg/l. Mixing in the reservoir could achieve substantial improvement in water quality. At this level of development, the fiftieth- and ninetieth-percentile values were the same for most months, meaning that the outflow would consist mostly of the return flows from irrigation. The average flows for each month, however, would be much higher than the fiftieth-percentile flow, showing the variability in the flow of the river.

Table 59. Outflow (in acre-feet) and TDS (in mg/l) of the Powder subbasin

Month	Level of Development							
	Low				55 Percent			
	Fiftieth Percentile	Ninetieth Percentile	Average	TDS	Fiftieth Percentile	Ninetieth Percentile	Average	TDS
Oct	2,000	2,000	5,856	2,079	3,000	3,000	3,363	3,799
Nov	1,250	1,250	6,542	1,630	1,800	1,800	2,706	3,226
Dec	1,000	1,000	4,673	1,937	1,500	1,500	2,356	3,216
Jan	750	750	4,257	1,976	1,130	1,130	2,085	3,000
Feb	2,982	500	13,043	1,036	750	750	6,136	1,402
Mar	34,922	750	61,954	739	1,130	1,130	46,946	750
Apr	30,600	3,315	43,997	1,061	19,797	1,500	30,941	1,149
May	51,484	16,066	55,376	1,096	31,586	4,040	38,324	1,310
June	84,438	3,500	102,888	1,028	63,416	5,260	89,507	1,116
July	4,500	4,500	20,483	1,552	6,760	6,760	14,383	3,372
Aug	4,500	4,500	4,970	3,548	6,760	6,760	6,760	8,089
Sept	2,500	2,500	3,667	3,145	3,760	3,760	3,760	4,084
TOTAL			327,706				247,267	

NOTE: See note to table 48.

In the 55 percent simulation, the outflows would consist mostly of irrigation return flows. The fiftieth-percentile flows would be high in the months of April, May, and June due to spring runoff and snowmelt in the upper portion of the basin. All ninetieth-percentile flows would be irrigation return flows. The irrigation projected for the 55 percent level would drastically degrade the water quality at the mouth of the river. The average TDS of inflows would be 1,200 mg/l, while that of the outflows would range from 1,100 to 4,000 mg/l in most months. Again, however, mixing in a reservoir could reduce TDS loads significantly.

THE LOWER YELLOWSTONE SUBBASIN

The water requirements projected for the high, intermediate, and low levels of development are given in table 60. These requirements include demands for irrigation, energy, and municipal use. No minimum flow was specified.

Inflow to the Lower Yellowstone Subbasin would be the sum of the outflows of the Powder and Kinsey Area Subbasins. Because no reservoir was assumed for the Lower Yellowstone Subbasin, the flows could not be stored or augmented.

Table 60. Lower Yellowstone subbasin water requirements (in acre-feet)

Month	Level of Development		
	Low	Intermediate	High
Oct	410	785	2,255
Nov	30	30	1,125
Dec	30	30	1,125
Jan	30	30	1,125
Feb	30	30	1,125
Mar	30	30	1,125
Apr	410	785	2,255
May	4,930	9,825	15,815
June	6,430	12,840	20,335
July	12,080	24,135	37,290
Aug	9,450	18,860	29,380
Sept	4,180	8,320	13,555
TOTAL	38,040	75,700	126,510

The results of the simulations are shown in table 61 and 62. The fiftieth- and ninetieth-percentile flows under all levels of development indicate that the demands could be satisfied but that a shortage would occur when demand exceeded inflow. A shortage would have occurred in August 1961 for all levels of development. The intermediate level of development would have less impact on flows than would the high level of development and the low level of development would have no significant impact.

TDS concentrations would increase, but even under the high level of development, average water quality would remain relatively good due to the high flows during periods of large irrigation return flows. During months of low flows, water quality degradation would be greater.

The simulations for the Lower Yellowstone Subbasin are important in that they represent the effect of all projected development in the Yellowstone Basin. The annual average outflow of the Lower Yellowstone Subbasin for the low, intermediate, and high levels of development would be 7,731,626 acre-feet, 7,623,890 acre-feet, and 7,279,803 acre-feet, respectively. The average annual outflow, 1944-73, was 8.317,411 acre-feet. On the average, there would be enough water to satisfy the projected demand, but in some months of some years there would not be enough even for low-level development, as indicated by the simulated shortage in August 1961.

Table 61. Outflow of the lower Yellowstone subbasin (in acre-feet)

Month	Level of Development					
	Low		Intermediate		High	
	Fiftieth Percentile	Ninetieth Percentile	Fiftieth Percentile	Ninetieth Percentile	Fiftieth Percentile	Ninetieth Percentile
Oct	453,165	305,608	450,778	305,093	437,762	294,921
Nov	441,005	340,600	422,969	337,869	410,592	325,594
Dec	350,824	234,670	339,545	231,366	325,177	217,052
Jan	316,982	201,851	301,589	198,777	295,093	183,233
Feb	338,537	249,182	329,219	243,590	313,099	228,098
Mar	612,714	304,539	512,839	296,179	574,039	279,314
Apr	538,938	388,858	513,823	363,422	496,380	346,372
May	1,037,764	480,471	1,001,548	440,103	953,657	387,916
June	2,217,203	1,123,425	2,155,473	1,101,047	2,091,092	1,051,323
July	1,085,902	393,907	1,049,411	358,134	961,489	296,861
Aug	353,761	138,179	323,394	109,601	251,367	48,601
Sept	326,062	174,059	309,139	160,003	266,401	98,503

NOTE: See note to table 48.

Table 62. Average outflow (in acre-feet) and TDS (in mg/l) of the lower Yellowstone subbasin

Month	Level of Development						Natural Flow
	Low		Intermediate		High		
	Flow	TDS	Flow	TDS	Flow	TDS	
Oct	466,078	552	459,071	561	445,522	570	504,187
Nov	439,383	577	429,514	585	417,049	594	452,667
Dec	339,180	636	331,424	640	317,270	646	354,445
Jan	321,902	648	314,522	653	299,309	664	342,515
Feb	377,602	565	363,556	572	346,679	579	396,331
Mar	652,078	496	613,719	504	607,521	508	707,417
Apr	588,151	538	564,206	544	547,420	548	617,821
May	988,728	368	943,250	377	893,574	386	1,050,604
June	2,304,475	291	2,240,210	291	2,186,485	291	2,379,886
July	1,231,810	304	1,179,488	307	1,091,427	313	1,420,334
Aug	384,481	451	353,748	458	284,934	482	483,946
Sept	345,388	557	327,167	566	282,328	583	426,303
TOTAL	8,439,256		8,119,875		7,719,518		9,136,456

Appendixes

Appendix A

PROJECTED WATER REQUIREMENTS IN THE YELLOWSTONE
RIVER BASIN IN THE YEAR 2000

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TABLE A-1. Monthly and annual water requirements in Upper Yellowstone subbasin, year 2000 under three levels of development (af).

	ENERGY		IRRIGATION[a]		MUNICIPAL		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
			LOW-LEVEL DEVELOPMENT[b]					
Jan								
Feb								
Mar								
Apr			380	250			380	250
May			4,950	3,300			4,950	3,300
Jun			6,470	4,315			6,470	4,315
Jul			12,180	8,125			12,180	8,125
Aug			9,520	6,350			9,520	6,350
Sep			4,190	2,790			4,190	2,790
Oct			380	250			380	250
Nov								
Dec								
ANNUAL			38,070	25,380			38,070	25,380
			INTERMEDIATE-LEVEL DEVELOPMENT[c]					
Jan								
Feb								
Mar								
Apr			760	510			760	510
May			9,900	6,600			9,900	6,600
Jun			12,950	8,630			12,950	8,630
Jul			24,370	16,250			24,370	16,250
Aug			19,040	12,695			19,040	12,695
Sep			8,380	5,585			8,380	5,585
Oct			760	510			760	510
Nov								
Dec								
ANNUAL			76,160	50,780			76,160	50,780
			HIGH-LEVEL DEVELOPMENT[d]					
Jan								
Feb								
Mar								
Apr			1,140	760			1,140	760
May			14,850	9,900			14,850	9,900
Jun			19,420	12,950			19,420	12,950
Jul			36,560	24,370			36,560	24,370
Aug			28,565	19,040			28,565	19,040
Sep			12,565	8,380			12,565	8,380
Oct			1,140	760			1,140	760
Nov								
Dec								
ANNUAL			114,240	76,160			114,240	76,160

[a]The irrigation diversion rate is 3 acre-feet/acre; the depletion rate is 2 acre-feet/acre.

[b]Assumptions: (no energy development); (12,690 acres of new irrigation)[e]; negligible increase in population.)

[c]Assumptions: (no energy development); (25,390 acres of new irrigation)[e]; negligible increase in population).

[d]Assumptions: (no energy development); (38,080 acres of new irrigation)[e]; negligible increase in population).

[e]Irrigation is assumed to be developed with loans at 10 percent amortized over 10 years.

TABLE A-2. Monthly and annual water requirements in Clarks Fork Yellowstone subbasin, year 2000 under three levels of development (af).

	ENERGY		IRRIGATION[a]		MUNICIPAL		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
			HIGH-LEVEL DEVELOPMENT[b]					
Jan								
Feb								
Mar								
Apr			65	40			65	40
May			840	560			840	560
Jun			1,100	735			1,100	735
Jul			2,080	1,385			2,080	1,385
Aug			1,620	1,085			1,620	1,085
Sep			710	475			710	475
Oct			65	40			65	40
Nov								
Dec								
ANNUAL			6,480	4,320			6,480	4,320

NOTE: The assumptions for both the low and intermediate levels of development were that there would be a negligible increase in energy development, population, and number of acres irrigated. Therefore, the amount of water depletion would also be negligible and is not shown.

[a]The diversion rate for irrigation is 3 acre-feet/acre; the depletion rate is 2 acre-feet/acre.

[b]Assumptions: negligible increase in energy development, population; irrigate 2,150 new acres[c].

[c]Assumptions: irrigation to be developed with loans at 10 percent amortized over 10 years.

TABLE A-3. Monthly and annual water requirements in Billings Area subbasin, year 2000 under three levels of development (af)

	ENERGY		IRRIGATION[a]		MUNICIPAL		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
			LOW-LEVEL DEVELOPMENT[d]					
Jan					580	290	580	290
Feb					580	290	580	290
Mar					580	290	580	290
Apr			195	130	580	290	775	420
May			2,525	1,680	580	290	3,105	1,970
Jun			3,300	2,200	580	290	3,880	2,490
Jul			6,210	4,140	580	290	6,790	4,430
Aug			4,850	3,235	580	290	5,430	3,525
Sep			2,135	1,425	580	290	2,715	1,715
Oct			195	130	580	290	775	420
Nov					580	290	580	290
Dec					580	290	580	290
ANNUAL			19,410	12,940	6,960	3,480	26,370	16,420
			INTERMEDIATE-LEVEL DEVELOPMENT[e]					
Jan					590	295	590	295
Feb					590	295	590	295
Mar					590	295	590	295
Apr			390	260	590	295	980	555
May			5,045	3,365	590	295	5,635	3,660
Jun			6,600	4,400	590	295	7,190	4,695
Jul			12,420	8,280	590	295	13,010	8,575
Aug			9,705	6,470	590	295	10,295	6,765
Sep			4,270	2,845	590	295	4,860	3,140
Oct			390	260	590	295	980	555
Nov					590	295	590	295
Dec					590	295	590	295
ANNUAL			38,820	25,880	7,080	3,540	45,900	29,420
			HIGH-LEVEL DEVELOPMENT[f]					
Jan					650	325	650	325
Feb					650	325	650	325
Mar					650	325	650	325
Apr			580	390	650	325	1,230	715
May			7,570	5,045	650	325	8,220	5,370
June			9,910	6,600	650	325	10,560	6,925
Jul			18,630	12,420	650	325	19,280	12,745
Aug			14,555	9,705	650	325	15,205	10,030
Sep			6,405	4,270	650	325	7,055	4,595
Oct			580	390	650	325	1,230	715
Nov					650	325	650	325
Dec					650	325	650	325
ANNUAL			58,230	38,820	7,800	3,900	66,030	42,720

[a] Agricultural irrigation diversion rate is 3 af/acre; depletion rate is 2 af/acre.

[b] Municipal water use at 200 gal/d/pers. for diversion; 100 gal/d/pers. depletion.

[c] Irrigation development carried on with 10 percent loans amortized over 10-year period.

[d] Assumptions: (no energy development); (6,470 new irrigated acres)[c]; (31,270 increase in population).

[e] Assumptions: (no energy development), (12,940 new irrigated acres)[c]; (31,804 increase in population).

[f] Assumptions: (no energy development), (19,410 acres new irrigation of feasible land)[c], (34,565 increase in population).

TABLE A-[illegible]. Monthly and annual water requirements in Bighorn subbasin, year 2000 under three levels of development (af).

	ENERGY		IRRIGATION[a]		MUNICIPAL[b]		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
			LOW-LEVEL DEVELOPMENT[d]					
Jan	70	70			Neg.	Neg.	70	70
Feb	70	70			Neg.	Neg.	70	70
Mar	70	70			Neg.	Neg.	70	70
Apr	70	70	130	90	Neg.	Neg.	200	160
May	70	70	1,700	1,130	Neg.	Neg.	1,770	1,200
Jun	70	70	2,220	1,480	Neg.	Neg.	2,290	1,550
Jul	70	70	4,180	2,785	Neg.	Neg.	4,250	2,855
Aug	70	70	3,260	2,175	Neg.	Neg.	3,330	2,245
Sep	70	70	1,435	960	Neg.	Neg.	1,505	1,030
Oct	70	70	130	90	Neg.	Neg.	200	160
Nov	70	70			Neg.	Neg.	70	70
Dec	70	70			Neg.	Neg.	70	70
ANNUAL	840	840	13,055	8,710	Neg.	Neg.	13,895	9,550
			INTERMEDIATE-LEVEL DEVELOPMENT[e]					
Jan	490	490			Neg.	Neg.	490	490
Feb	490	490			Neg.	Neg.	490	490
Mar	490	490			Neg.	Neg.	490	490
Apr	490	490	260	175	Neg.	Neg.	750	665
May	490	490	3,390	2,260	Neg.	Neg.	3,880	2,750
Jun	490	490	4,430	2,955	Neg.	Neg.	4,920	3,445
Jul	490	490	8,340	5,560	Neg.	Neg.	8,830	6,050
Aug	490	490	6,520	4,345	Neg.	Neg.	7,010	4,835
Sep	490	490	2,870	1,910	Neg.	Neg.	3,360	2,400
Oct	490	490	260	175	Neg.	Neg.	750	665
Nov	490	490			Neg.	Neg.	490	490
Dec	490	490			Neg.	Neg.	490	490
ANNUAL	5,880	5,880	26,070	17,380	Neg.	Neg.	31,950	23,260
			HIGH-LEVEL DEVELOPMENT[f]					
Jan	2,345	2,345			80	40	2,425	2,385
Feb	2,345	2,345			80	40	2,425	2,385
Mar	2,345	2,345			80	40	2,425	2,385
Apr	2,345	2,345	390	260	80	40	2,815	2,645
May	2,345	2,345	5,085	3,390	80	40	7,510	5,775
Jun	2,345	2,345	6,650	4,430	80	40	9,075	6,815
Jul	2,345	2,345	12,520	8,345	80	40	14,945	10,730
Aug	2,345	2,345	9,785	6,525	80	40	12,210	8,910
Sep	2,345	2,345	4,300	2,870	80	40	6,725	5,255
Oct	2,345	2,345	390	260	80	40	2,815	2,645
Nov	2,345	2,345			80	40	2,425	2,385
Dec	2,345	2,345			80	40	2,425	2,385
ANNUAL	28,140	28,140	39,120	26,080	960	480	68,220	54,700

[a] Agricultural irrigation diversion rate is 3 af/y/acre; depletion rate is 2 af/acre.

[b] Municipal water use at 200 gal/d/pers. for diversion; 100 gal/d/pers. depletion.

[c] Irrigation development carried on with 10 percent loans amortized over 10-year period.

[d] Assumptions: (17.1 mmt strip mine increase); (4,435 new irrigated acres)[c]; (2,334 increase in population).

[e] Assumptions: (5.9 mmt slurry, 29.3 mmt strip mines increase); (8,690 new irrigated acres)[c]; (3,145 increase in population).

[f] Assumptions: (1-1,000 mw 14.8 mmt slurry, 36.9 mmt strip mines increase); (13,040 acres new irrigation of feasible land)[c].

TABLE A-5. Monthly and annual water requirements in Mid-Yellowstone subbasin, year 2000 under three levels of development (af).

	ENERGY		IRRIGATION[a]		MUNICIPAL[b]		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
				LOW-LEVEL DEVELOPMENT[d]				
Jan	2,930	2,930			280	140	3,210	3,070
Feb	2,930	2,930			280	140	3,210	3,070
Mar	2,930	2,930			280	140	3.210	3,070
Apr	2,930	2,930	250	170	280	140	3,460	3,240
May	2,930	2,930	3,280	2,190	280	140	6,490	5,260
Jun	2,930	2,930	4,290	2,860	280	140	7,500	5,930
Jul	2,930	2,930	8,075	5,380	280	140	11,285	8,450
Aug	2,930	2,930	6,310	4,200	280	140	9,520	7,270
Sep	2,930	2,930	2,775	1,850	280	140	5,985	4,920
Oct	2,930	2,930	250	170	280	140	3,460	3,240
Nov	2,930	2,930			280	140	3,210	3,070
Dec	2,930	2,930			280	140	3,210	3,070
ANNUAL	35,160	35,160	25,230	16,820	3,360	1,680	63,750	53,660
				INTERMEDIATE-LEVEL DEVELOPMENT[e]				
Jan	6,290	6,290			310	155	6,600	6,445
Feb	6,290	6,290			310	155	6,600	6,445
Mar	6,290	6,290			310	155	6,600	6,445
Apr	6,290	6,290	505	335	310	155	7,105	6,780
May	6,290	6,290	6,560	4,375	310	155	13,160	10,820
Jun	6,290	6,290	8,580	5,720	310	155	15,180	12,165
Jul	6,290	6,290	16,150	10,765	310	155	22,750	17,210
Aug	6,290	6,290	12,610	8,410	310	155	19,210	14,855
Sep	6,290	6,290	5,550	3,700	310	155	12,150	10,145
Oct	6,290	6,290	505	335	310	155	7,105	6,780
Nov	6,290	6,290			310	155	6,600	6,445
Dec	6,290	6,290			310	155	6,600	6,445
ANNUAL	75,480	75,480	50,460	33,640	3,720	1,860	129,660	110.980
				HIGH-LEVEL DEVELOPMENT[f]				
Jan	11,620	11,620			645	320	12,265	11,940
Feb	11,620	11,620			645	320	12,265	11,940
Mar	11,620	11,620			645	320	12,265	11,940
Apr	11,620	11,620	760	505	645	320	13,025	12,445
May	11,620	11,620	9,840	6,560	645	320	22,105	18,500
Jun	11,620	11,620	12,870	8,580	645	320	25,135	20,520
Jul	11,620	11,620	24,215	16,150	645	320	36,480	28,090
Aug	11,620	11,620	18,920	12,610	645	320	31.185	24,550
Sep	11,620	11,620	8,325	5,550	645	320	20,590	17,490
Oct	11,620	11,620	760	505	645	320	13,025	12,445
Nov	11,620	11,620			645	320	12,265	11,940
Dec	11,620	11,620			645	320	12,265	11,940
ANNUAL	139,440	139,440	75,690	50,460	7,740	3,840	222,870	193,740

[a]Agricultural irrigation diversion rate is 3 af/acre; depletion rate is 2 af/acre.

[b]Municipal water use at 200 gal/d/pers. for diversion; 100 gal/d/pers. depletion.

[c]Irrigation development carried on with 10 percent loans amortized over 10 year period.

[d]Assumptions: (15-1,000 mw, 1-250 mmcfdgas, 59.9 mmt strip mines new development); (8,410 new irrigated acres)[c]; (15,887 increase in population).

[e]Assumptions: (3-1,000 mw, 1-250 mmcfd gas, 20.5 mmt slurry, 102.6 mmt strip mines); (16,820 new irrigated acres)[c]; (17,771 increase in population).

[f]Assumptions: (3-1,000 mw, 2-250 mmcfd gas, 1-100,000 b/d syn-crude, 51.6 mmt slurry, 128.9 mmt strip); (25,230 acres new irrig of feasible land)[c]; (36,250 increase population).

[illegible]

	Energy		Irrigation[a]		Municipal[b]		Total	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
				LOW-LEVEL DEVELOPMENT[d]				
Jan	955	955			Neg.	Neg.	955	955
Feb	955	955			Neg.	Neg.	955	955
Mar	955	955			Neg.	Neg.	955	955
Apr	955	955	500	345	Neg.	Neg.	1,4[illegible]	1,[illegible]
May	955	955	2,[illegible]	1,[illegible]	Neg.	Neg.	[illegible]	[illegible]
Jun	955	955	[illegible]	[illegible]	Neg.	Neg.	[illegible]	[illegible]
Jul	955	955	[illegible]	[illegible]	Neg.	Neg.	[illegible]	[illegible]
Aug	955	955	[illegible]	[illegible]	Neg.	Neg.	[illegible]	[illegible]
Sep	955	955	[illegible]	1,61[illegible]	Neg.	Neg.	[illegible]	[illegible]
Oct	955	955	[illegible]	[illegible]	Neg.	Neg.	[illegible]	[illegible]
Nov	955	955			Neg.	Neg.	955	955
Dec	955	955			Neg.	Neg.	955	955
ANNUAL	11,460	11,460	21,9[illegible]	14,6[illegible]	Neg.	Neg.	33,4[illegible]	26,1[illegible]
				INTERMEDIATE-LEVEL DEVELOPMENT[e]				
Jan	3,900	3,900			60	30	3,960	3,930
Feb	3,900	3,900			60	30	3,960	3,930
Mar	3,900	3,900			60	30	3,960	3,930
Apr	3,900	3,900	440	290	60	30	4,40[illegible]	4,220
May	3,900	3,900	[illegible]	[illegible]	60	30	[illegible]	[illegible]
Jun	3,900	3,900	7,4[illegible]	[illegible]	60	30	11,[illegible]	[illegible]
Jul	3,900	3,900	14,16[illegible]	9,3[illegible]	60	30	18,[illegible]	13,[illegible]
Aug	3,900	3,900	13,7[illegible]	7,31[illegible]	60	30	17,[illegible]	11,24[illegible]
Sep	3,900	3,900	[illegible]	[illegible]	60	30	8,7[illegible]	7,1[illegible]
Oct	3,900	3,900	440	290	60	30	4,40[illegible]	4,220
Nov	3,900	3,900			60	30	3,960	3,930
Dec	3,900	3,900			60	30	3,960	3,930
ANNUAL	46,800	46,800	43,[illegible]	29,[illegible]	720	360	91,41[illegible]	76,42[illegible]
				HIGH-LEVEL DEVELOPMENT[f]				
Jan	9,835	9,835			130	65	9,965	9,900
Feb	9,835	9,835			130	65	9,965	9,900
Mar	9,835	9,835			130	65	9,965	9,900
Apr	9,835	9,835	680	440	130	65	10,6[illegible]	10,340
May	9,835	9,835	8,[illegible]	5,710	130	65	18,[illegible]	15,6[illegible]
Jun	9,835	9,835	11,1[illegible]	7,4[illegible]	130	65	21,1[illegible]	17,36[illegible]
Jul	9,835	9,835	[illegible]	14,[illegible]	130	65	31,[illegible]	23,[illegible]
Aug	9,835	9,835	16,440	11,[illegible]	130	65	26,4[illegible]	[illegible]
Sep	9,835	9,835	7,24[illegible]	4,33[illegible]	130	65	17,21[illegible]	14,7[illegible]
Oct	9,835	9,835	680	440	130	65	10,6[illegible]	10,340
Nov	9,835	9,835			130	65	9,965	9,900
Dec	9,835	9,835			130	65	9,965	9,900
ANNUAL	118,0[illegible]	118,0[illegible]	6[illegible]	43,910	1,560	780	18[illegible],43[illegible]	162,7[illegible]

[a]Agricultural irrigation diversion rate is 3 af/acre; depletion rate is 2 af/acre.

[b]Municipal water use at 200 gal/d/pers. for diversion; 100 gal/d/pers. depletion.

[c]Irrigation development carried on with 10 percent [illegible] over [illegible]-year period.

[d][illegible]

[e][illegible]

[f][illegible]

TABLE A-7. Monthly and annual water requirements in Kinsey Area subbasin, year 2000 under three levels of development (af)

	ENERGY		IRRIGATION[a]		MUNICIPAL		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
			LOW-LEVEL DEVELOPMENT[c]					
Annual			4,740	3,160			4,741	3,160
			INTERMEDIATE-LEVEL DEVELOPMENT[d]					
Jan								
Feb								
Mar								
Apr			95	60			95	60
May			1,230	820			1,230	820
Jun			1,610	1,075			1,610	1,075
Jul			3,035	2,025			3.035	2,025
Aug			2,375	1,585			2,375	1,585
Sep			1,040	695			1,040	695
Oct			95	60			95	60
Nov								
Dec								
ANNUAL			9,480	6,320			9,480	6,320
			HIGH-LEVEL DEVELOPMENT[e]					
Jan								
Feb								
Mar								
Apr			140	95			140	95
May			1,850	1,230			1,850	1,230
Jun			2,420	1,610			2,420	1,610
Jul			4,555	3,035			4,555	3,035
Aug			3,550	2,375			3,550	2,375
Sep			1,565	1,040			1,565	1,040
Oct			140	95			140	95
Nov								
Dec								
ANNUAL			14,220	9,480			14,220	9,480

[a]Agricultural irrigation diversion rate is 3 af/acre; depletion rate is 2 af/acre.

[b]Irrigation development carried on with 10 percent loans amortized over 10 year period.

[c]Assumptions: (no energy development); (1,580 new irrigated acres)[b]; (neg. increase in population).

[d]Assumptions: (no energy development); (3,160 new irrigated acres)[b]; (neg. increase in population).

[e]Assumptions: (no energy development); (4,740 acres new irrigation of feasible land)[b]; (neg. increase in population).

TABLE A-8. Monthly and annual water requirements in Powder subbasin, year 2000 under three levels of development (af)

	ENERGY		IRRIGATION[a]		MUNICIPAL[b]		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
			LOW-LEVEL DEVELOPMENT[d]					
Jan	70	70			Neg.	Neg.	70	70
Feb	70	70			Neg.	Neg.	70	70
Mar	70	70			Neg.	Neg.	70	70
Apr	70	70	750	500	Neg.	Neg.	820	570
May	70	70	9,780	6,520	Neg.	Neg.	9,850	6,590
Jun	70	70	12,785	8,525	Neg.	Neg.	12,855	8,595
Jul	70	70	24,070	16,045	Neg.	Neg.	24,140	16,115
Aug	70	70	18,800	12,535	Neg.	Neg.	18,870	12,605
Sep	70	70	8,275	5,515	Neg.	Neg.	8,345	5,585
Oct	70	70	750	500	Neg.	Neg.	820	570
Nov	70	70			Neg.	Neg.	70	70
Dec	70	70			Neg.	Neg.	70	70
ANNUAL	840	840	75,210	50,140	Neg.	Neg.	76,050	50,980
			INTERMEDIATE-LEVEL DEVELOPMENT[e]					
Jan	1,570	1,570			100	50	1,670	1,620
Feb	1,570	1,570			100	50	1,670	1,620
Mar	1,570	1,570			100	50	1,670	1,620
Apr	1,570	1,570	1,500	1,000	100	50	3,170	2,620
May	1,570	1,570	19,555	13,040	100	50	21,225	14,660
Jun	1,570	1,570	25,570	17,050	100	50	27,240	18,670
Jul	1,570	1,570	48,140	32,090	100	50	49,810	33,710
Aug	1,570	1,570	37,610	25,070	100	50	39,280	26,690
Sep	1,570	1,570	16,545	11,030	100	50	18,215	12,650
Oct	1,570	1,570	1,500	1,000	100	50	3,170	2,620
Nov	1,570	1,570			100	50	1,670	1,620
Dec	1,570	1,570			100	50	1,670	1,620
ANNUAL	18,840	18,840	150,420	100,280	1,200	600	170,460	119,725
			HIGH-LEVEL DEVELOPMENT[f]					
Jan	1,800	1,880			190	95	2,070	1,975
Feb	1,880	1,880			190	95	2,070	1,975
Mar	1,880	1,880			190	95	2,070	1,975
Apr	1,880	1,880	2,255	1,500	190	95	4,325	3,475
May	1,880	1,880	29,330	19,550	190	95	31,400	21,525
Jun	1,880	1,880	38,350	25,570	190	95	40,420	27,545
Jul	1,880	1,880	72,190	48,130	190	95	74,260	50,105
Aug	1,880	1,880	56,405	37,605	190	95	58,475	39,580
Sep	1,880	1,880	24,815	16,545	190	95	26,885	18,520
Oct	1,880	1,880	2,255	1,500	190	95	4,325	3,475
Nov	1,880	1,880			190	95	2,070	1,975
Dec	1,880	1,880			190	95	2,070	1,975
ANNUAL	22,560	22,560	225,600	150,400	2,280	1,140	250,440	174,100

[a]Agricultural irrigation diversion rate is 3 af/acre; depletion rate is 2 af/acre.

[b]Municipal water use at 200 gal/d/pers. for diversion, 100 gal/d/pers. depletion.

[c]Irrigation development carried on with 10 percent loads amortized over 10-year period.

[d]Assumptions: (17.1 mmt strip mines); (25,070 new irrigated acres)[c]; (3,339 increase in population).

[e]Assumptions: (1-100 mw, 5.9 mmt slurry); (29.3 mmt strip mines); (50,140 new irrigated acres)[c]; (5,297 increase in population).

[f]Assumptions: (1-1,000 mw, 14.8 mmt slurry); (36.9 mmt strip mines); 75-200 acres new irrigation of feasible land)[c]; (9,893 increase in population).

TABLE A-9. Monthly and annual water requirements in Lower Yellowstone subbasin, year 2000 under three levels of development (af)

	ENERGY		IRRIGATION[a]		MUNICIPAL[b]		TOTAL	
	Divert	Deplete	Divert	Deplete	Divert	Deplete	Divert	Deplete
			LOW-LEVEL DEVELOPMENT[d]					
Jan					60	30	60	30
Feb					60	30	60	30
Mar					60	30	60	30
Apr			380	250	60	30	440	280
May			4,900	3,270	60	30	4,960	3,300
Jun			6,400	4,270	60	30	6,460	4,300
Jul			12,050	8,040	60	30	12,110	8,070
Aug			9,420	6,280	60	30	9,480	6,310
Sep			4,150	2,760	60	30	4,210	2,790
Oct			380	250	60	30	440	280
Nov					60	30	60	30
Dec					60	30	60	30
ANNUAL			37,680	25,120	720	360	38,400	25,480
			INTERMEDIATE-LEVEL DEVELOPMENT[e]					
Jan					60	30	60	30
Feb					60	30	60	30
Mar					60	30	60	30
Apr			755	500	60	30	815	530
May			9,795	6,525	60	30	9,855	6,555
Jun			12,810	8,535	60	30	12,870	8,565
Jul			24,105	16,070	60	30	24,165	16,100
Aug			18,830	12,550	60	30	18,890	12,580
Sep			8,290	5,520	60	30	8,350	5,550
Oct			755	500	60	30	815	530
Nov					60	30	60	30
Dec					60	30	60	30
ANNUAL			75,340	50,200	720	360	76,060	50,560
			HIGH-LEVEL DEVELOPMENT[f]					
Jan	1,085	1,085			80	40	1,165	1,125
Feb	1,085	1,085			80	40	1,165	1,125
Mar	1,085	1,085			80	40	1,165	1,125
Apr	1,085	1,085	1,130	755	80	40	2,295	1,880
May	1,085	1,085	14,690	9,795	80	40	15,855	10,920
Jun	1,085	1,085	19,210	12,810	80	40	20,375	13,935
Jul	1,085	1,085	36,165	24,100	80	40	37,330	25,225
Aug	1,085	1,085	28,255	18,830	80	40	29,420	19,955
Sep	1,085	1,085	12,430	8,290	80	40	13,595	9,415
Oct	1,085	1,085	1,130	755	80	40	2,295	1,880
Nov	1,085	1,085			80	40	1,165	1,125
Dec	1,085	1,085			80	40	1,165	1,125
ANNUAL	13,020	13,020	113,010	75,335	960	480	126,990	88,835

[a]Agricultural irrigation diversion rate is 3 af/acre, depletion rate is 2 af/acre.

[b]Municipal water use at 200 gal/d/pers. for diversion, 100 gal/d/pers. depletion.

[c]Irrigation development carried on with 10 percent loans amortized over 10-year period.

[d]Assumptions: (no energy development); (12,560 new irrigated acres)[c]; (3,381 increase population).

[e]Assumptions: (no energy development); (25,100 new irrigated acres)[c]; (3,381 increase in population).

[f]Assumptions: (1-2,300 t/d fertilizer plant); (37,670 acres new irrigation of feasible land)[c]; (4,125 increase in population).

Appendix B

CO-EFFICIENTS AND CONSTANTS FOR SUBBASIN MODEL RUNS

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TABLE B-1. Temperature-independent coefficients

Coefficients	Subbasins								
	Upper Yellowstone	Clarks Fork	Billings Area	Bighorn	Mid-Yellowstone	Tongue	Kinsey Area	Powder	Lower Yellowstone
C(3,2)	.020893	.017610	.034310	.26370	.004255	.003570	.035561	.004262	.013678
C(3,3)	.000347	.000294	.000731	.000110	.000090	.000110	.000741	.000089	.000285
C(3,6)	.000367	.000294	.000731	.000110	.000090	.000110	.000741	.000089	.000285
C(3,11)	-1.0	-1.0	-24.0	-1.0	- .80	- .60	-24.0	- .40	- .80
C(3,19)	.010450	.008805	.017155	.013185	.002128	.001785	.017781	.002131	.000839
C(3,28)	0.0	0.0	- .034310	- .026370	- .002128	- .001785	- .035561	- .004262	- .013678
C(4,12)	- .7	- .427	-6.0	-1.3	-1.0	-1.0	-6.0	-2.0	-1.0
C(4,32)	.037402	.009147	.049167	.033125	.004473	.003660	.079521	.004473	.019016

TABLE B-2. Temperature-dependent coefficients

Coefficients	Temperature less than 32°F								
	Upper Yellowstone	Clarks Fork	Billings Area	Bighorn	Mid-Yellowstone	Tongue	Kinsey Area	Powder	Lower Yellowstone
C(1,2)	.25EL	.25EL	.50EL	.25EL	.25EL	.25EL	.5EL	.25EL	.25EL
C(1,19)	.50EL	.5EL	.5EL	.50EL	.5EL	.5EL	.5EL	.50EL	.5EL
C(1,28)	- .25EL	- .5EL	- .5EL	- .25EL	- .25EL	- .25EL	- .5EL	- .25EL	- .25EL
C(1,31)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(1,32)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(3,31)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(4,9)	- .00067	.00055	- .005666	- .0022	- .0002	- .0002	- .005829	- .0002	.0002
C(4,10)	- .00067	.00055	- .005666	- .0022	- .0002	- .0002	- .005829	- .0002	.0002
C(5,15)	.024	.024	12	.012	.012	.012	p	.012	.012
C(5,16)	.024	.024	12	.012	.012	.012	p	.012	.012
C(6,22)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(6,31)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
C(7,13)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(7,15)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(8,12)	.4-.5EL	.4-.5EL	.5-.5EL	.5-.5EL	.4-.5EL	.5-.5EL	.5-.5EL	.4-.5EL	[illegible]
C(8,28)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(9,5)	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	[illegible]
C(9,12)	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	[illegible]
C(9,17)	5.0EL	5.0EL	.5EL	5.0EL	5.0EL	.5EL	.5EL	5.0EL	[illegible]
C(9,28)	.8EL	.8EL	1.0EL	1.0EL	.8EL	.8EL	1.0EL	[illegible]	[illegible]
C(10,12)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(10,28)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(11,31)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(12,22)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(14,21)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(14,22)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(14,23)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

p = .004 X EXP (.06 X (32 - T))
r = .004 X EXP (.205043 X (32 - T))
EL = evaporation loss

TABLE B-3. Temperature-dependent coefficients

Coefficients	Temperature greater than $32^{o}F$								
	Upper Yellowstone	Clarks Fork	Billings Area	Bighorn	Mid-Yellowstone	Tongue	Kinsey Area	Powder	Lower Yellowstone
C(1,2)	EL	1.0EL	.5EL	.75EL	1.0EL	1.0EL	.5EL	1.0EL	1.0EL
C(1,19)	EL	1.0EL	.5EL	.5EL	1.0EL	1.0EL	.5EL	1.0EL	1.0EL
C(1,28)	- .25EL	- .25EL	- .5EL	- .25EL	- .25EL	- .25EL	.5EL	- .25EL	- .25EL
C(1,31)	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL
C(1,32)	EVP	EVP	.5EL	EVP	0.0	EVP	.5EL	EVP	EVP
C(3,31)	.010450	.010450	.017155	.019185	.013792	.001785	.0017781	.002128	.006839
C(4,19)	- .00097	- .00097	- .005666	- .002792	- .001666	- .000254	- .005829	- .000307	- .000338
C(4,10)	- .00097	- .00097	- .005666	- .002792	- .001666	- .000254	- .005829	- .000307	- .000338
C(5,15)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(5,16)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(8,22)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C(6,31)	0.0	0.0	0.0.	0.0	0.0	0.0	0.0	0.0	0.0
C(7,13)	.5A	.5A	.5A	.5A	.5A	.5A	.5A	.5A	.5A
C(7,15)	A	A	A	A	A	A	A	A	A
C(8,12)	.4-.5EL	.4-.5EL	.5-.5EL	.5-.5EL	.4-.5EL	.5-.5EL	.5-.5EL	.4-.5EL	.4-.5EL
C(8,28)	.3-.8EL	.3-.8EL	.3-EL	.3-.8EL	.3-.8EL	.3-.8EL	.3-EL	.3-.8EL	.3-.8EL
C(9.5)	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL	5.0EL
C(9,12)	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL	.5EL
C(9,17)	5.0EL	5.0EL	.5EL	5.0EL	5.0EL	5.0EL	.5EL	5.0EL	5.0EL
C(9,28)	.8EL	.8EL	EL	EL	.5EL	.8EL	EL	.8EL	.8EL
C(10,12)	.5	.5	.5	.5	.5	.5	.5	.5	.5
C(19,28)	.7	.7	.7	.7	.7	.7	.7	.7	.7
C(11,31)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
C(12,22)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C(16,21)	.5d	.5d	.5d	.5d	.5d	.5d	.5d	.5d	.5d
C(16,22)	.5d	.5d	.5d	.5d	.5d	.5d	.5d	.5d	.5d
C(16,23)	d	d	d	d	d	d	d	d	d

EVP is calculated in Sub routine SURFACE and transferred to mainline.

EL = evaporation loss
A = snowmelt rate
d = dampening factor

TABLE B-4. Temperature-dependent coefficients

Constants*

$$D = SF \frac{(X5 + X23)}{(d + X5 + X23)}$$

$$A = \frac{C(T-32)K6 + (T-32)^2}{(bK6) + b^2} + K7\left(X5 + \frac{X15}{2}\right)$$

$$FL = CT + dT^2$$

$$X13 = \left(1 - \frac{T-G}{32}\right) X5 \text{ when } 32 \le T \le M$$

$$X13 = 0 \text{ when } T > M$$

$$X13 = \frac{M - T}{N\ P}\ X5 \text{ when } G \le T \le 32\text{; except in Powder Subbasin, where } X13 = 1 - SQRT\left(\frac{T-G}{24}\right) X5$$

$$X13 = X5 \text{ when } T < G$$

Constants	Subbasins								
	Upper Yellowstone	Clarks Fork	Billings Area	Bighorn	Mid-Yellowstone	Tongue	Kinsey Area	Powder	Lower Yellowstone
SF	.01865	.036	.034029	.1470	.02120	.03145	.0036	.012578	.0758
b	31.0	31.0	13.0	13.0	10.0	13.0	10.0	10.0	10.0
K6	20.0	20.	50.	50.0	50.0	40.0	30.0	40.0	30.
K7	.05	.05	.12	.07	.12	.05	.05	.07	.05
C	14×10^{-5}	14×10^{-5}	11.8×10^{-5}	12×10^{-5}	11.8×10^{-5}	13.4×10^{-5}	14×10^{-5}	16×10^{-5}	14×10^{-5}
d	45×10^{-7}	45×10^{-7}	12.5×10^{-7}	43×10^{-7}	12.5×10^{-7}	47.2×10^{-7}	45×10^{-7}	90×10^{-7}	45×10^{-7}
F	16.0	16.0	32.0	20.0	32.0	16.0	16.0	14.0	14.0
G	16.0	16.0	32.0	20.0	32.0	16.0	12.0	14.0	12.0
M	40.0	40.0	81.0	40.0	81.0	40.0	40.0		40.0
N	10.5	10.5	49.0	10.5	49.0	10.5	10.5		10.5
P	3.0	3.0	2.0	3.0	2.0	3.0	3.0		3.0

*D = soil water percolation
A = rate of snowmelt
T = temperature in Fahrenheit
X13 = snowfall
X5 = precipitation
X23 = initial soil water storage

Table B-5. Initial values
(independent of the scenario)

Subbasins	RE	Q	SAVE	FC	FCMin	Q1	Q2	P1	P2	M	N
Billings Area	.40	.85	.24370	.825	.0825	.015	.015	.006623	.005956	1944	1973
Bighorn	.40	.80	.317350	.94	.094	.02	.02	.056322	.054806	1944	1973
Mid-Yellowstone	.40	.85	.396737	1.125	.1125	.015	.015	.010118	.009549	1944	1973
Tongue	.40	.80	.015368	.852	.03834	.015	.015	.000435	.000417	1944	1973
Powder	.40	.80	.305471	.830	.083	.015	.015	.000457	.000549	1944	1973
Lower Yellowstone	.40	.80	.358272	1.66	.166	.010	.010	.095730	.087535	1944	1973

Table B-6. Initial values
(dependent on the scenario)

Subbasins	Scenario	S3	STD2	EN
Billings Area	High	0.0	0.0	0.0
	Inter.	0.0	0.0	0.0
	Low	0.0	0.0	0.0
Bighorn	High	1.1	1.1	.002345
	Inter.	1.1	1.1	.000490
Mid-Yellowstone	High	0.0	0.0	.011620
	Inter.	0.0	0.0	.006290
	Low	0.0	0.0	.002930
Tongue	High	.32	.32	.004385
	Inter.	.32	.32	.003900
	Low	.112	.112	.000955
Powder	Inter.	.275	.275	0.0
	Low	.275	.275	.000070
Lower Yellowstone	High	0.0	0.0	.001085
	Inter.	0.0	0.0	0.0
	Low	0.0	0.0	0.0

Appendix C

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TABLE C-1. Yellowstone River at Billings: regression equations

Month	Best Fit Equation	r^2	Significance
Jan	log TDS = 3.16424 - .12912 log Q	.073	NS
Feb	log TDS = 3.54116 - .20614 log Q	.106	NS
Mar	TDS = 1527.71 - 235.17461 log Q	.766	**
Apr	log TDS = 4.24384 - .34054 log Q	.645	**
May	TDS = 924.22705 - 131.16983 log Q	.606	**
June	log TDS = 2.57791 - .08230 log Q	.063	NS
July	TDS = 935.46143 - 135.05623 log Q	.827	**
Aug	log TDS = 4.27605 - .35261 log Q	.850	**
Sept	TDS = 1622.26001 - 251.31508 log Q	.868	**
Oct	log TDS = 5.05812 - .48689 log Q	.834	**
Nov	TDS = 2255.61938 - 368.94141 log Q	.806	**
Dec	TDS = 2119.83569 - 346.26465 log Q	.510	**
ALL MONTHS	log TDS = 4.82194 - .44798 log Q	.934	**

NOTE: TDS = Average Monthly Total Dissolved Solids, mg/l

Q = Monthly Discharge, acre feet

** = Significant at 1% level

* = Significant at 5% level

NS = Not Significant at 5% level

TABLE C-2. Tongue River near Miles City: regression equations

Month	Best Fit Equations	r^2	Significance
Jan	log TDS = 2.968046 - .00001178 Q	.373	**
Feb	log TDS = 2.8869196 - .0000093196 Q	.718	**
Mar	TDS = 1445.71 - 217.25081 log Q	.539	**
Apr	TDS = 1524.68 - 217.70712 log Q	.867	**
May	TDS = 1348.75 - 191.64864 log Q	.546	**
June	TDS = 1221.21 - 189.03383 log Q	.750	**
July	TDS = 1513.50 - 260.70199 log Q	.815	**
Aug	TDS = 1686.28 - 301.87476 log Q	.819	**
Sept	log TDS = 3.51775 - .20078 log Q	.869	**
Oct	TDS = 1647.14 - 265.4541 log Q	.787	**
Nov	TDS = 3.69492 - .21753	.627	**
Dec	TDS = 2375.20 - 408.74805	.420	**
ALL MONTHS	TDS = 1672.10 - 267.88599 log Q	.583	**

NOTE: TDS = Average Monthly Total Dissolved Solids, mg/l

Q = Monthly Discharge, acre feet

** = Significant at 1% level

* = Significant at 5% level

NS = Not Significant at 5% level

TABLE C-3. Powder River at Locate: regression equations

Month	Best Fit Equations	r^2	Significance
Jan	TDS = 2009.9 - .04002 Q	.154	NS
Feb	TDS = 3965.75 - 663.84961 log Q	.745	**
Mar	log TDS = 3.14148 - .0000027288 Q	.857	**
Apr	TDS = 1603.99 - .00769 Q	.764	**
May	TDS = 2952.23 - 408.35352 log Q	.179	NS
June	log TDS = 3.50657 - .10353 log Q	.256	NS
July	TDS = 4378.26 - 707.0542 log Q	.580	*
Aug	TDS = 2171.01 - 136.30793 log Q	.067	NS
Sept	log TDS = 3.35371 - .06055 log Q	.170	NS
Oct	TDS = 3479.57 - 521.59961 log Q	.517	NS
Nov	log TDS = 3.37988 - .00002 Q	.855	**
Dec	log TDS = 3.40523 - .00002 Q	.749	**

NOTE: TDS = Average Monthly Total Dissolved Solids, mg/l

Q = Monthly Discharge, acre feet

** = Significant at 1% level

* = Significant at 5% level

NS = Not Significant at 5% level

TABLE C-4. Big Horn River: regression equation

Monthly Values for TDS_{SX} are		
Jan = 551	Feb = 589	March = 609
Apr = 602	May = 610	June = 590
July = 527	Aug = 447	Sept = 475
Oct = 604	Nov = 567	Dec = 571

NOTE: $TDS = 57.1 + .93596\ TDS_{SX}$

where TDS = Average Monthly Total Dissolved Solids, mg/l

TDS_{SX} = TDS near St. Xavier

TABLE C-5. Yellowstone near Miles City: regression equation

$$\text{Log TDS} = 5.7522 - .545 \log Q$$

where TDS = Average Monthly Total Dissolved Solids in mg/l

Q = Monthly Discharge in acre feet

TABLE C-6. Yellowstone River near Sidney: regression equations

Month	Best Fit Equation	r^2	Significance
Jan	log TDS = 4.45663 - .2983 log Q	.655	**
Feb	TDS = 2469.44 - 339.72412	.580	**
Mar	TDS = 2785.62 - 392.1665	.571	*
Apr	log TDS = 2.83667 - .0000001614 Q	.634	**
May	TDS = 561.71 - .00017959 Q		
June	TDS = 198.98 + .00003539 Q		
July	TDS = 917.41 - 101.69664 log Q	.250	
Aug	TDS = 2303.31 - 327.66333 log Q	.602	**
Sept	log TDS = 2.85842 - .0000002973 Q	.543	*
Oct	TDS = 3745.50 - 561.71338 log Q	.722	**
Nov	TDS = 3852.08 - 579.99414 log Q	.629	**
Dec	TDS = 754.84 - .000344 Q	.446	NS

NOTE: TDS = Average Monthly Total Dissolved Solids, mg/l

Q = Monthly Discharge, acre feet

** = Significant at 1% level

* = Significant at 5% level

NS = Not Significant at 5% level

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